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FAST AND FLEXIBLE COMMUNICATION OF ENGINEERING INFORMATION IN THE AEROSPACE INDUSTRY

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
77 MASSACHUSETTS AVENUE
CAMBRIDGE, MA 02139-4307

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FINAL REPORT FOR 06/17/1994 – 01/31/1998

MATERIALS AND MANUFACTURING DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE OH 45433-7750

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George B. Orzel

GEORGE B. ORZEL
Project Engineer
Industrial Infrastructure Team
Mfg. & Engineering Systems Branch

Brenchley L. Boden

BRENCHLEY L. BODEN II
Acting Leader
Industrial Infrastructure Team
Mfg. & Engineering Systems Branch

Patrick E Price

PATRICK E. PRICE
Acting Chief
Mfg. & Engineering Systems Branch
Manufacturing Technology Division

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This program was launched together with a sister program called Fast and Flexible Communication in the Auto Industry to explore ways of improving the design and manufacture of complex products in an environment of globalization, outsourcing, information technology, increased international competition, and shrinking defense budgets. The research was conducted in the context of Agile Manufacturing, which seeks to improve the performance of companies operating together in fast-changing environments. The opportunity to conduct research on the seemingly disparate auto and aircraft industries proved to be very beneficial, because it was found that these industries share many of the same problems and can learn a great deal from each other.

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CONTENTS

LIST OF FIGURES

1. Foreward

This is the final report on the program Fast and Flexible Communication of Engineering Information in the Aerospace Industry, Air Force Contract number F33615-94-C-4429, administered by Wright Laboratory/MTIA. Mr George Orzel served as Air Force Program Manager. The period of performance was June 17, 1994 through January 31, 1998. This program was funded as part of DARPA's effort in Agile Manufacturing, under the direction of Dr Michael McGrath. The prime contractor was the Massachusetts Institute of Technology. The work was conducted by members of the Mechanical Engineering Department, Sloan School of Management, and Center for Technology, Policy, and Industrial Development. The Principal Investigator was Dr Daniel E Whitney. Participating organizations included The Vought Center of Northrop-Grumman Corp, Boeing Commercial Airplane Group, Lockheed-Martin Ft Worth Division, and the Ford Motor Company. This program shared some participants with a sister program called Fast and Flexible Communication in the Automotive Industry: Lehigh University Department of Mechanical Engineering, General Motors Delphi Saginaw Division, Mid-Lux Division, and Die Management Group, and Ford Visteon Electronics Division. Technical contributions were made by Mr Martin Anderson, Mr Carlo Cadet, Prof Charles Fine, Prof David Gossard, Prof Anna Thornton, and Dr Daniel Whitney, plus graduate students Timothy Cunningham, Ramakrishna Mantripragada, Jeffrey Adams, Don Lee, Tariq Shaukat, Mary Ann Anderson, Richard Keiser, Richard Seubert, Steven Llorente, Kenneth Gayer, and Brian Kelley. The researchers thank Mrs Gina Milton for administrative assistance, good cheer, and encouragement.

2. Executive Summary

This program was launched together with a sister program called Fast and Flexible Communication in the Auto Industry to explore ways of improving the design and manufacture of complex products in an environment of globalization, outsourcing, information technology, increased international competition, and shrinking defense budgets. The research was conducted in the context of Agile Manufacturing, which seeks to improve the performance of companies operating together in fast-changing environments. The opportunity to conduct research on the seemingly disparate auto and aircraft industries proved to be very beneficial, because it was found that these industries share many of the same problems and can learn a great deal from each other.

Both programs focused on the design, development, and manufacture of complex electro-mechanical assemblies such as automotive bodies, electronic assemblies, and aircraft structure. Such products challenge their manufacturers because they have many parts, tight tolerances, and high performance standards. It is common that 50 to 75% by value or part count is outsourced. In spite of great progress in computer-aided design (CAD) and information technology (IT), problems still occur on the assembly line during production ramp-up and daily production.

Mechanical assemblies are a good focus for this kind of research because they exhibit what may be called *integration problems*. Assembly is inherently integrative, and assembly problems are proxies for a wide variety of technical, organizational, and managerial problems encountered in the design and manufacture of high technology products in the military and commercial worlds. What we learn about improving the design of assemblies can be translated to a considerable degree to other highly integral products.

A basic assumption behind this project is that factory floor problems can often, perhaps mostly, be traced to errors or missing information stemming from product design. Important goals of this project were therefore to improve the agility of manufacturing companies by determining what this missing information might be, documenting the technical and managerial efforts companies are using to provide and utilize this information, understanding the barriers to improved methods, and developing new methods based on research that is grounded in case studies with partner companies.

From the basic assumption, we developed our research approach, which began in every partner company with projects on the factory floor. Here we learned about actual assembly problems and traced some of them to their causes. We also documented the corrective action processes at different

companies and compared not only their content but the degree to which corrective action personnel could draw on design data to help them solve their problems. Finally, we developed some new analysis and design methods.

Here are the specific problems we found:

- Product design in the auto and aircraft industries takes from 3 to 10 years and may involve companies thousands of miles apart; a great deal of information is created and exchanged during this time, and the opportunity for errors is large

- There is a wide range of performance between the companies in the auto industry and the aircraft industry in the design and procurement of complex assemblies, with adoption of best practices in the auto industry leading that in the aircraft industry by as much as 7 years

- Many industries have adopted variants on the method of Key Characteristics (KCs) for defining product quality and communicating it to their employees and companies in their supply chain; performance in implementing this method varies widely across companies, and it is generally considered a promising but still evolving method

- Key design decisions that affect assembly floor performance (speed, rework time, first time yield, cost) are made as early as the concept design phase, but these decisions may occur unconsciously or as unseen parts of other decisions; once the design proces passes to later phases, it operates within the chosen concept for good or ill, and there is little opportunity to change it

- Commonly used CAD tools do not support either key decisions during concept design or the top-down design of assemblies; adequate CAD support exists only at the detail part level, which is too low in the work breakdown structure (WBS) to capture and influence the important integration issues that affect agility

- Companies that develop and partially outsource complex products face what we call "integration risk:" the risk that apparently correctly designed and made components will not function together properly as a system; companies lack adequate tools to identify integration risk during concept design, the time when decisions that create this risk are made

- Integrated product teams (IPTs) consist of people from very different technical and non-technical backgrounds, and their contributions during concept design in particular span a very wide range of strategic, tactical,

business, and technical issues; these people lack a common language for dealing with many key concept design issues

• Any new computer tools that intend to aid IPTs in addressing issues with high leverage on agility will have to be understandable by all IPT members regardless of their functional background

To address these issues, the program conducted the following research and case studies:

1. Historical study of the development of assembly dimensional control methods in the auto industry, with emphasis on the combination of technical, organizational, and managerial elements necessary for successful implementation (Section 4.4)

2. Assessment of the maturity of the KC method in 22 companies in a variety of industries, followed by development of a KC maturity model and establishment of a multi-industry working group and a series of annual conferences (Section 5)

3. Development of a method for capturing key product architecture decisions during concept design of complex assemblies, improving the ability of a multi-function IPT to assess degrees of integration risk inherent in different concepts as an aid to concept selection and risk mitigation; application of this method in a case study of Joint Strike Fighter (JSF) concept selection (Section 7)

4. Development of a top-down design process for assemblies, including development of new assembly modeling techniques, dimensional control methods, tolerance definitions, and computer methods for developing and evaluating assembly processes (Section 8)

5. Comparison of corrective action methods in assembly between an auto company and an aircraft company (Section 9)

6. Study of new skills and training requirements for factory floor workers in an environment of fixtureless assembly (Section 10)

7. Development of a fixtureless assembly process for skins of aircraft wing-like assemblies: concept mechanical fabrication and assembly process design, redesign of key dimensional features on parts, concept design of equipment, tolerance analysis of competing processes, factory floor operating simulation, and financial justification of competing processes and business scenarios (Section 11)

8. Creation of a set of prototype assembly design and analysis computer tools (Section 12)

9. Creation of a new course in Mechanical Engineering called Mechanical Assembly and its Role in Product Development, incorporating many of the lessons and new methods that emerged from this program (Appendix 1)

3. Introduction

3.1. *Motivation and History*

3.1.1. Agile manufacturing

The aim of this program was to apply some of the principles of Agile Manufacturing [Goldman, Nagel, Preiss] to problems of large scale manufacturing of complex products. One of the aims of Agility is to improve communications between customers and suppliers. It is apparent that these communications are presently hampered by a lack of reliable technologies for exchanging files in common formats. Although progress is being made on this front, it is also true that other problems exist that cannot be solved even by perfect file exchange technologies. These problems exist not only at the technical level but also at the organizational and managerial levels. Design documents do not necessarily contain the necessary information. People with different functional backgrounds or organizational loyalties do not always share vocabularies and motivations, and thus either cannot really understand each other or may not be able to act appropriately.

Our goals in this research were to

- Understand how to improve complex customer-supplier relationships, using assemblies as an example

- Compare methods and performance of the auto and aircraft industries

- Develop new methods and tools

- Develop metrics

- Test the tools and metrics in partner companies

This research was originally based on two hypotheses:

1. Important blockages of information flow can be identified by examining business processes and looking for places in the process that exhibit "interaction intensity"

2. Important technical information about mechanical and other items can be captured in "features" which are, at a minimum, standardized geometric elements with associated information about use, processing, etc.

In pursuit of the first hypothesis, we developed tools to map information flows and identify transaction intensity in a systematic way. In

pursuit of the second hypothesis, we created methods of modeling complex assemblies and showed how their interactions could be captured during design and preserved for later participants in the process of bringing products to production. These are listed in Section 3.3 and explained in detail later in the report.

We see the causes of poor communication in two forms: either the information is corrupted at points of interaction intensity or else it is missing from the beginning. We see the consequences on the factory floor where it takes too long to assemble products, or there is too much rework, or it takes too long to ramp production up to full rate. However, we do not see this as the fault of the factory or its workers. Instead we see the problem stemming from the lack of critical information that should have been provided during the design process. (For example, [Ceglarek and Shi] report that 27% of root causes in 52 automotive body assembly problems were due to design related problems. During ramp-up, design-related problems accounted for 43%. Problems related to suppliers almost equal those due to design. Our own research produced similar results.)

Therefore, a restatement of the problem is: what is the missing information from design that contributes so much to loss of agility in the assembly of complex products? What we found is:

- products are procured from a complex web of companies spread far apart geographically

- this trend is accelerating

- complex products contain hundreds of assemblies and thousands of parts, the majority of which are purchased from chains of distant suppliers who may design as well as make them

- the problem facing any company in this chain is managing the process, including defining and managing interfaces among all the outsourced items

- factors affecting the quality of a complex product arise from the design and operation of *sets* of parts, rather than from one or a few key parts

- when a product fails to deliver the required quality, either during design, production ramp-up, or full rate production, it is extremely difficult to find out why because many parts or assemblies and many suppliers are involved, and a consistent, readily understood map of their interactions has not been created

Therefore, the key missing information revolves around descriptions of how sets of parts are intended to work together. Either the product was designed without planning the overall performance in a top-down way or else the design intent for achieving overall quality was not captured and communicated to the suppliers and final assemblers in sufficient form and detail to permit design, procurement, and assembly to proceed in a fast and flexible manner.

The above properties of modern product development and manufacturing are illustrated in Figure 3-1.

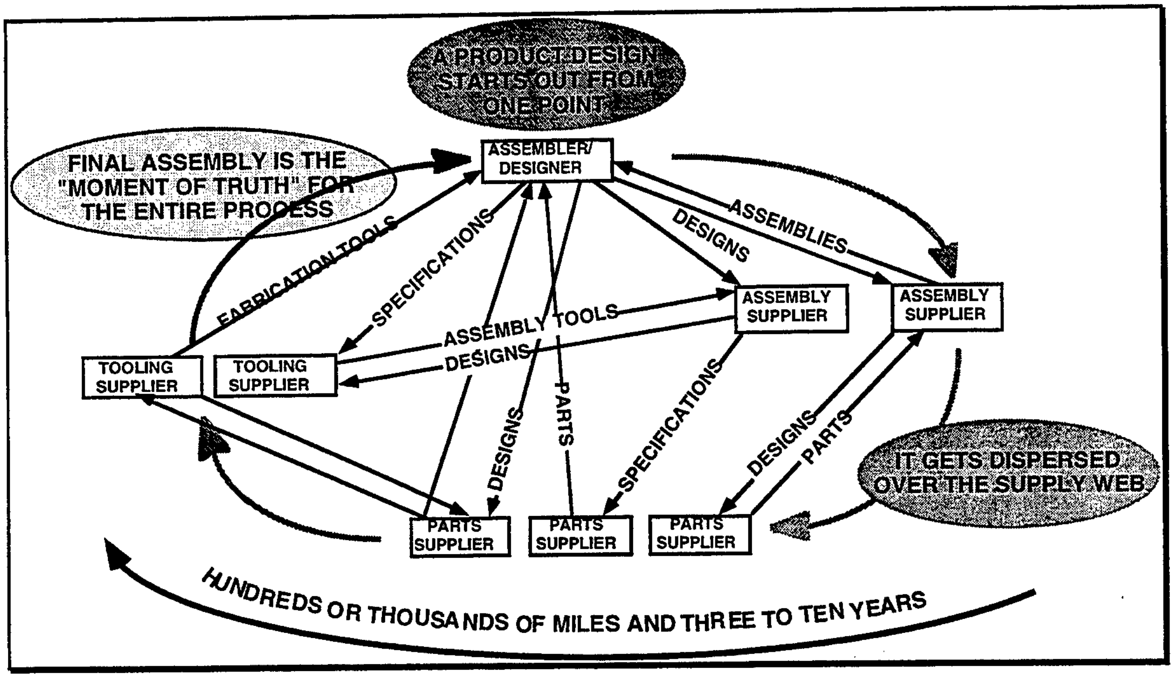

Figure 3-1. Complex Products Are Procured from a Complex Web of Companies. This web is not tiered and the items exchanged include information, things, and people.

3.1.2. Aero and auto programs at MIT

MIT has conducted studies on fast and flexible manufacturing in the auto and aircraft industries in parallel.[1] The benefit of having these two projects is the ability to share research methods, send students and research staff to companies in both industries, and compare findings. To a surprisng degree, we find the same causes and effects in both industries. Both have large and far-flung supply chains, develop complex electro-mechanical products, work to a high standard of quality and tolerances, and have to create a complex but cost-effective and safe product. Both industries have been leaders in design technologies.

[1] The Auto program has prepared a separate final report.

Again, to a surprising degree, the two industries share problems and solution methods. The major differences are that the auto industry may have a faster learning curve because it can design more products and can expose its design and manufacturing employees to more learning experiences in a given time. Furthermore, the car industry has a faster production rate and thus cannot ignore a factory floor problem for more than a few minutes, whereas the aircraft industry often takes weeks or months to recognize a problem and find a solution.

People in the aircraft industry often say that the car industry can invest more in design and production technology because of the benefit of high production rates. The situation is in fact the opposite: a high production rate forces the car industry to solve problems quickly and to develop the necessary technology.[2] In fact, as will be described below, we believe that in a number of areas the car industry is ahead of the aircraft industry:

- organization of the product development process to create top-down dimensional control plans for assemblies,

- managerial sophistication to form partnerships with suppliers of assemblies and the necessary equipment, tooling, and fixturing,

- ability to follow up designs and plans,[3] and

- use of systematic procedures for diagnosing and fixing assembly plant errors.

In fact, it is precisely because learning opportunities are fewer in the aircraft industry that it must do more during design to reduce integration risk.

3.1.3. Focus on procurement of complex mechanical assemblies from a supply chain

To limit the scope of this research without losing generality, we focused on complex mechanical assemblies. Assemblies share many of the properties of systems in general. They have many components which work together in complex ways to create the system's overall behavior. More importantly, they

[2] In fact, a crude economic argument can be made that the amount of money involved in car and commercial aircraft production is about the same, approximately $2.5 billion of final sales per year per assembly line. That is, a typical car assembly line makes 125,000 units per year at $20,000 retail price per car; Boeing's annual sales of $25 billion divided by 5 major assembly lines yields $2.5 billion per line per year.

[3] An expert in this area at a car company said "First you have to make the plan, and then you have to ride herd on the plan."

share with systems in general the property of *non-co-location of cause and effect*, which means simply that the symptom can be here while the cause is "way over there." One of the major cultural barriers to improving speed and flexibility in procurement of assemblies is to convince people that a problem in an assembly is not the fault of the last part installed. A broad view is needed that requires access to design intent and the processes and behavior of many people at many companies.

A knowledgeable person at one of our auto partner companies said "We design parts, we don't design assemblies." This company actually does much better than that, but the point is clear and we found symptoms of it at most of our partner companies. We call it being "part-centric." Part-centric design focuses, as the name implies, on detailed design of individual parts and leaves til later, if ever, the problem of deciding how the parts are to go together. This approach has been encouraged unintentionally by the rising ability of three dimensional computer-aided design (3D CAD) to enable this phase of design without corresponding support for design of assemblies. We frequently encountered the opinion that "We will use 3D CAD and so we won't have any problems during assembly." Or "I thought 3D CAD had eliminated shims." Or "The product just snaps together."

The fact is that 3D CAD can eliminate gross errors in the design (the equivalent of mean shifts in manufacturing) but it cannot eliminate manufacturing and assembly variation. Electronic parts are always the right size, so electronic pre-assembly always works. As so many companies have found out, eliminating variation requires different methods and important organizational and cultural shifts.

All these considerations justify our studying assemblies as indicators of how the product development process and supply chain work in general and how to make improvements that are effective at the system level.

3.2. Methodology

3.2.1. Case studies and field sites

The research methodology followed in this project was to form relationships with a number of companies in the auto and aircraft industries, identify design and manufacturing sites, and place students there for extended periods of time, usually every summer and every January. Shorter visits were made in between. In some cases, the students were interns in the MIT Leaders for Manufacturing program, in which case they spent 6 months on site at a host company. Faculty supervisors made repeated visits while the students were on site and kept up communication via electronic mail. Figure 3-2 diagrams the partnerships developed in the two MIT programs while Table 3-1 lists the field projects in more detail.

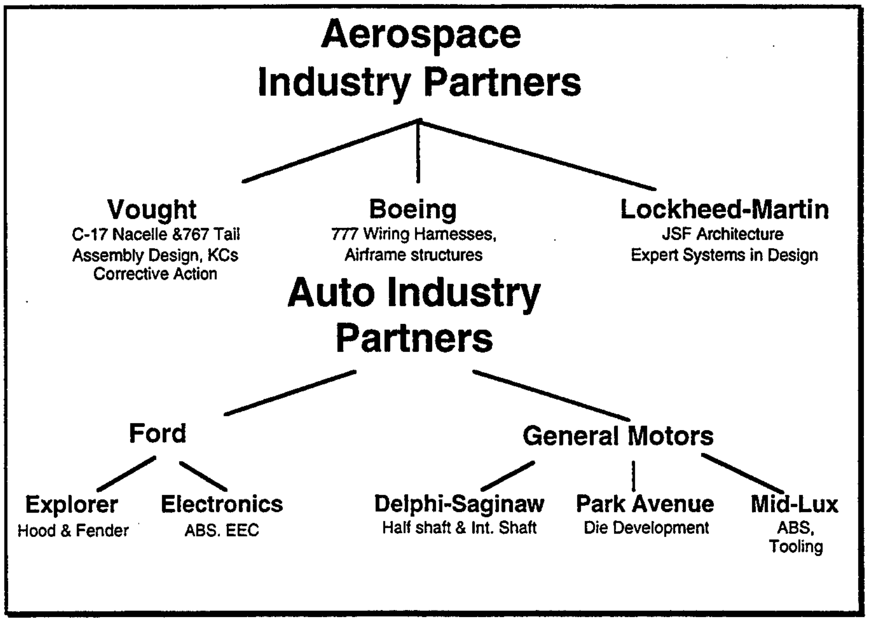

Figure 3-2. Industry Partners and Project Foci

Field Project(s)	Site	Tool developed or tested	Major lessons
Corrective Action in assembly (2)	Ford and Northrop Grumman Vought Center	Contact chains	Need design intent info and systematic CA process to make CA fast
Precision Assembly of 767 Horiz Stabilizer Skin (2)	Northrop Grumman Vought Center	Contact chain, KCs, assembly sequence analysis, VSA, cost analysis	Need process capability data and design intent data to permit rationalized process design
Outsourcing of major aircraft tooling	Boeing	Supply chain and cost analysis	Need cultural and organizational change to enable win-win customer-supplier relationships
KC case studies and maturity model	22 companies	KC Maturity model	KC maturity is low
Org learning for precision assembly	Northrop-Grumman Vought Center	Design Structure Matrix	Precision assembly requires diagnostic skills rather than manual skills
Modeling of assembly layouts for top-down design and process planning (3)	Ford, Northrop Grumman Vought Center, Boeing, Kawasaki Heavy Industries	Datum Flow Chain, CAD models of assemblies, tolerance chains	Benefit of simple diagrams that emphasize how KCs are delivered

Identification of integration risk during concept design	Lockheed Martin Ft Worth	Contact Chain, System Producibility Analysis, ChainMetrics Method	Product architecture and integration risk can be estimated using data available during concept design

Table 3-1. Field Research Projects Listed by Site, Tools Used, and Lessons. Each of the tools and many of the projects are described in detail later in this report.

3.2.2. Project Organization

This project was organized around the assumption that information and knowledge have a natural flow in a manufacturing company. This flow starts out with customer requirements leading to design specifications and designs. These designs are prepared for manufacturing, and production is launched. During production ramp-up, problems occur and corrective actions are instituted. Learnings from corrective action and later production are (or should be) recycled back to the design process for subsequent products. This cycle can be likened to the plan-do-check-act cycle attributed to Deming.

In the case of this project, the cycle can be illustrated in Figure 3-3.

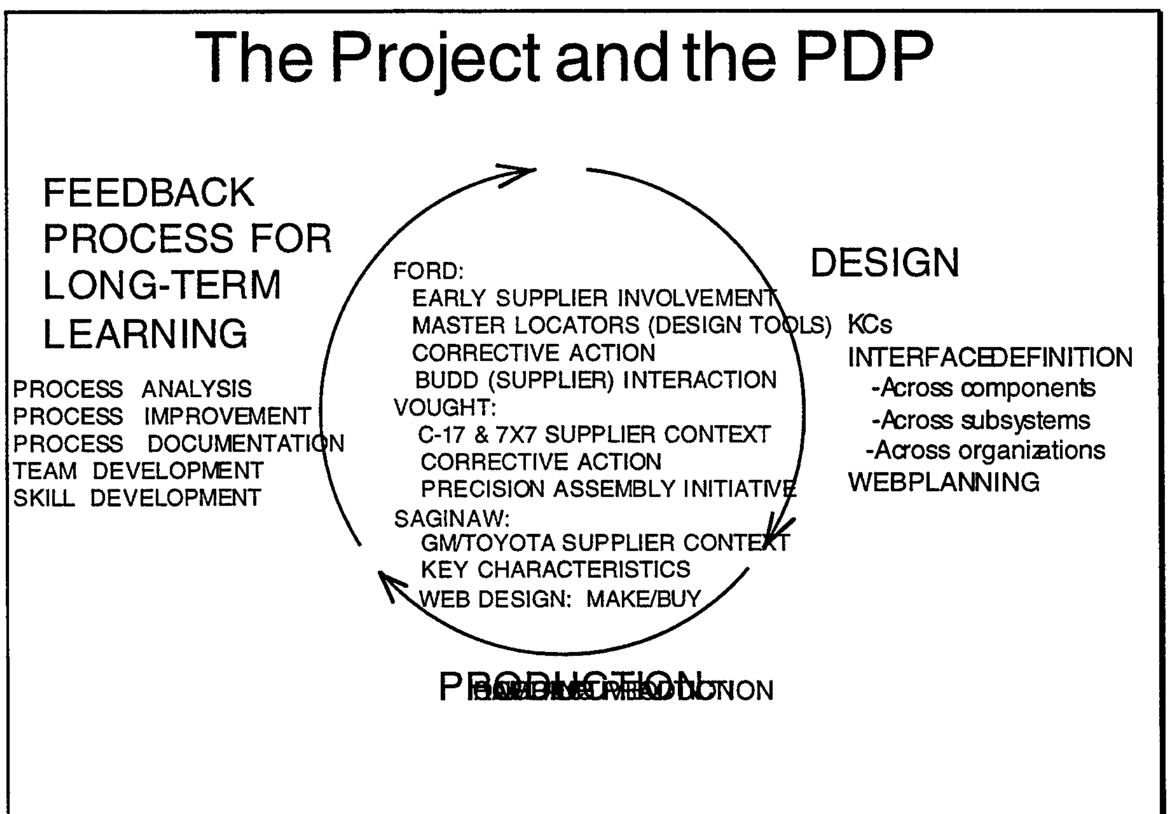

Figure 3-3. Mapping of this Project onto the Product Development Process (PDP) in the Format of Plan-Do-Check-Act. Sevaral example activities within the project are shown, along with the tools and methods used.

3.3. Multiple lenses and tools developed

The research emphasized the need to combine technical, organizational, and managerial issues. In order to do this, we developed a number of "lenses" through which we viewed the problem of procuring complex assemblies from a web of suppliers. The lenses are:

Key Characteristics (KCs) -- A product feature lens that identifies important customer requirements and expresses them in engineering specifications

Web Maps -- A supply network lens that indicates which suppliers are responsible for which elements of the chain of parts and assemblies that deliver a Key Characteristic

Design Structure Matrix (DSM) -- An information flow mapping lens that shows how different tasks and product design team members exchange information

Contact Chains -- A physical product lens that maps which parts participate in delivering a Key Characteristic

Activity Cost Chains -- A cost/DFM lens that traces costs to the activities necessary to deliver the KC

Feature-based Design for Assembly -- A physical model lens that permits assemblies to be described in CAD

Each of these lenses emphasizes a different aspect of the problem. The relationship of these tools to the basic problems of product development is shown in Figure 3-4.

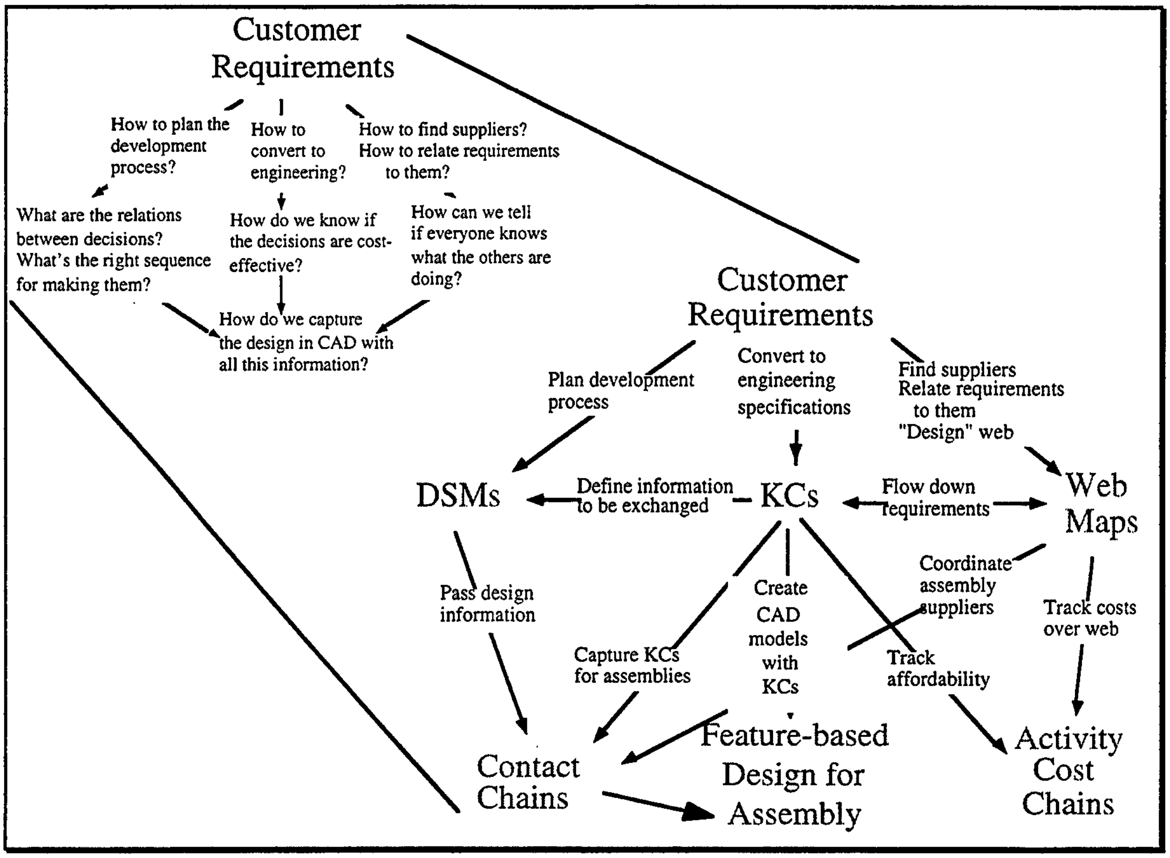

Figure 3-4. Tools Developed in this Project and Their Relationship to Basic Questions in Product Development

The upper left of Figure 3-4 shows the challenges faced by product developers while the lower right shows the tools developed during this research for addressing them. Product development begins with identifying customer requirements and planning a response in three domains: performance (in the middle of the figure), product development planning (at the left), and identification of partners and suppliers (at the right). Across the middle are three coordination issues that highlight the problem of relating steps in the development process, decisions in the design process, and communciation in the supply chain. At the bottom is the question of implementing better product development in new computer tools.

At the lower right of Figure 3-4 is the same diagram populated with names of tools or methods developed or adopted and improved during this research. At the left is the DSM, or Design Structure Matrix, a method of recording the fact that different steps or participants in the process exchange information either in a feed forward or a feedback way. Few people have a high level view of the design process they are involved in, and the DSM has proven valuable in providing that view and enabling re-engineering of processes to streamline information exchange. In the middle are Key

Characteristics (KCs) that capture customer requirements that could be at risk due to variation. Identification and flowdown of KCs is a newly emerging way to systematically distribute requirements to subassemblies, suppliers, and individual parts so that top-level quality is obtained. Web maps are diagrams of suppliers and what items they make. (See Figure 3-5) Contact chains illustrate which parts touch each other in the process of combining to deliver a KC. Such maps are invaluable for designing assemblies so that they in fact succeed in delivering KCs and for helping the diagnostic process when there are problems on the assembly line. The most informative web maps have the contact chain superimposed on them so that everyone can see their role in delivering the KCs. Feature-based design permits CAD systems to capture KCs and contact chains so that quantitative design data necessary for design and analysis are integrated with geometric models. Activity cost chains permit activity-based costing to be applied to contact chains to determine the cost of delivering a KC.

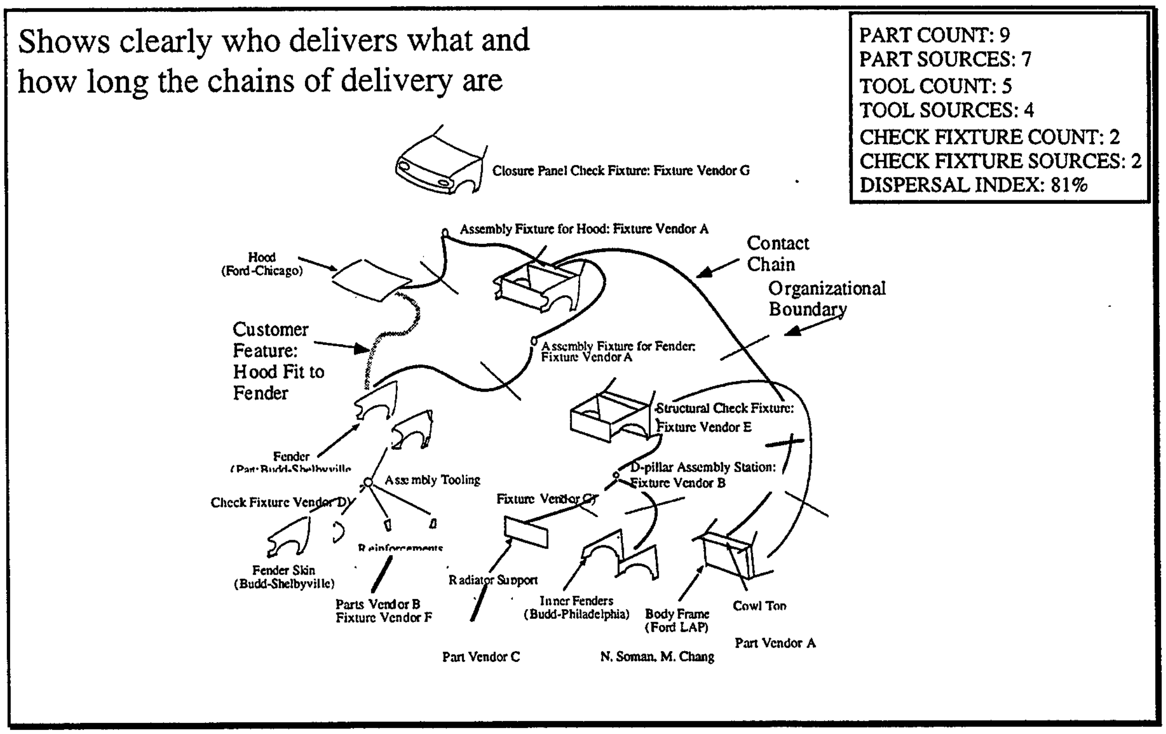

Figure 3-5. A Web Map of an Automobile Front End Customer Requirement. This map diagrams a real product and indicates the high degree of outsourcing involved in both parts and tooling. In a qualitative way, this diagram superimposes a tolerance chain onto the supply chain. Without maps like this, line workers have a hard time diagnosing assembly problems.

3.3.1. Specific tools developed or used: DSM, DFC, SPA

3.3.1.1. The Design Structure Matrix

A design structure matrix [Steward], [Eppinger et al] is a square array that permits diagramming of task, information, design parameter, or people interactions. Unlike the hierarchical IDEF models, DSMs are flat. Basic relationships and clusters of tasks (similar to intensive clusters of transactions) show up vividly on a DSM and can be seen easily by almost anyone regardless of their technical background. Figure 3-6 shows a simple DSM and defines basic terms. Figure 3-7 illustrates canonical patterns of task interactions that are made visible by a DSM.

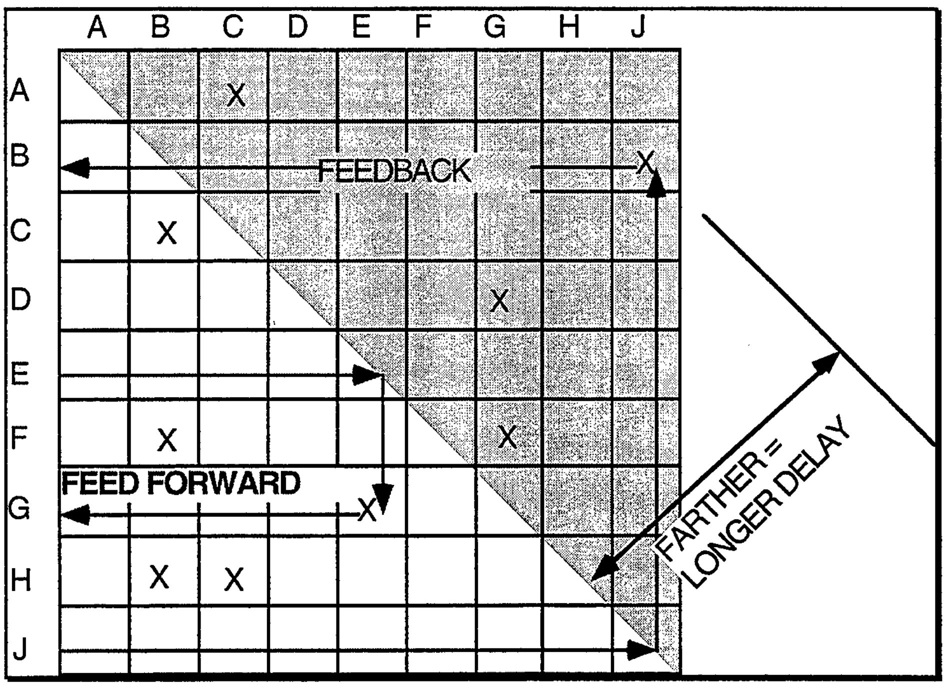

Figure 3-6. Basic Design Structure Matrix. Tasks are listed across the top and down the side in the nominal sequence of execution. An X in a cell means that the task along the top passes information to the task down the side (E to G, or J to B). Xs below the diagonal pass information forward while Xs above pass it back. Thus the DSM can capture structural iteration and repetition of tasks. Sometimes it is possible to rearrange or split tasks in order to make information flow more efficient, eliminate iteration, or shorten feedback loops.

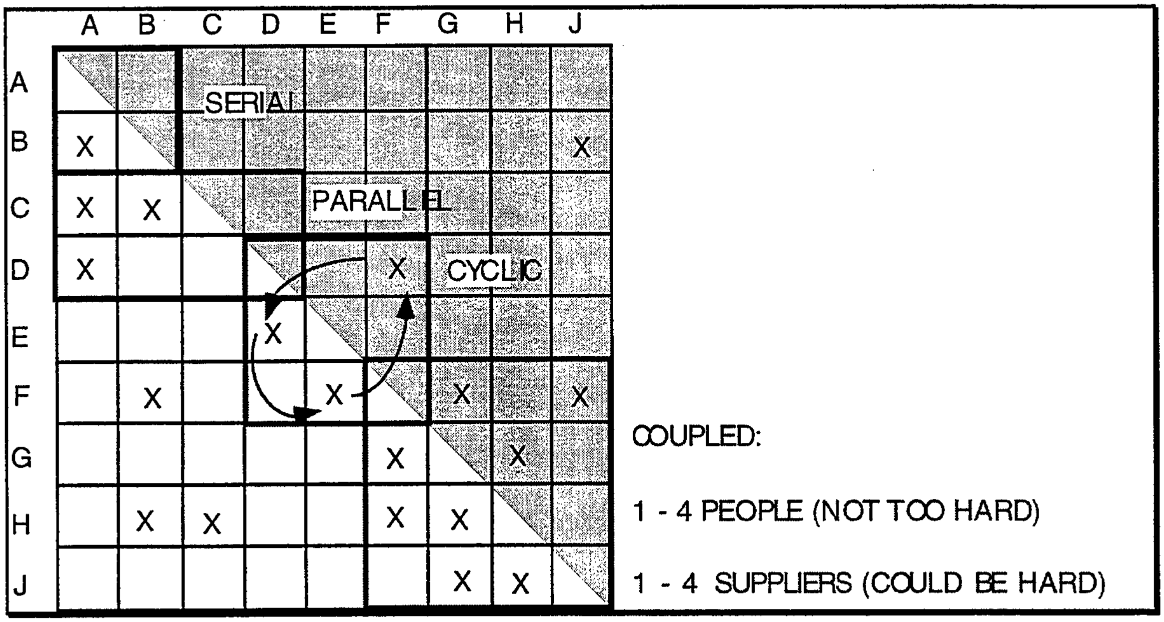

Figure 3-7. A DSM Can Represent Four Classic Kinds of Task Interactions: Serial, parallel, cyclic or iterative, and coupled.

DSMs have been used for the following purposes in this research and other projects:

- present as-is processes to their participants in order to encourage improvements

- verify that specific KCs are being designed for delivery by a coherent process

- identify bottlenecks in processes and focus management attention on them

- identify interactions between parameters needed or measured during assembly and the upstream workstations where those parameters were set

- show who should participate in team meetings intended to resolve certain issues or design specific items that deliver a particular KC

- advise architects and facility designers who are arranging space for design teams so that communication is easy for people whose activities are closely related

- provide traceability from decisions to supporting analyses or earlier decisions to aid design rationale and design reviews

3.3.1.2. The Datum Flow Chain

A datum flow chain (DFC) is a directed acyclic graph that indicates how parts locate each other in space. It has one root, which is the primary datum (in a base part or a fixture) and contains nodes that represent parts or fixtures and arcs that represent passing of dimensional location and constraint from part to part or fixture to part. A DFC contains the logic of the assembly layout and captures the designer's intent for how one or more KCs will be delivered. When fixture-based assembly methods are used, the DFC typically contains the fixtures. A DFC contains information about which degrees of freedom on a part are constrained by one or more other parts. At each interface between parts one can assign an assembly feature that constrains those degrees of freedom. One can also apply tolerances to each arc and thus analyze the robustness of KC delivery. Thus the DFC combines three kinds of design intent: dimensional location strategy, constraint, and tolerance analysis.

3.3.1.3. The System Producibility Analysis Method

The System Producibility Analysis method (SPA) utilizes a qualitative version of the DFC to permit members of an IPT with diverse backgrounds to discuss alternate ways of achieving KCs during concept design. Concept design is the most fertile and formative phase of the product development process. During this stage, customer requirements are converted into specific functional requirements, which are in turn converted into trial physical embodiments. These embodiments comprise the architecture of the product, that is, the definition of the physical elements and the interrelations between them. In different physical concepts, these relationships may be more or less complex as well as more or less capable of delivering the required performance and more or less easy to assemble and test. Each of the main participants in the IPT (performance designers, producibility engineers, and outsourcing strategists) will evaluate each concept differently according to their needs. The SPA method allows them to diagram KC deliverability systematically using a set of symbols that they all can understand, and allows them to evaluate each concept to estimate its degree of integration risk: the likelihood that the constituent parts and systems, even when made properly, will not function together as intended.

3.4. Summary of Results, Findings and Recommendations

3.4.1. Importance of the data provided by the design process

Advanced companies have realized that the early stages of product development are the most creative and important because they set the conditions for later phases and for production. Concurrent engineering or integrated product teams (IPTs) consist of widely different constituencies with different motivations, concerns, reward structures, and languages. The most

prominent during actual design are those representing performance, producibility, and strategy (technology for product and process plus identification of key suppliers and partners). Each of these constituencies provides rationale for important decisions regarding design concepts, outsourcing, and production methods. These decisions and the rationale behind them are needed by later participants as they weigh tradeoffs or diagnose problems. Today's design processes and supporting computer tools are inadequate to capture and structure all the information and make it accessible.

3.4.2. Importance of a top-down approach

A top-down approach to product development starts with customer requirements for performance and cost, and proceeds systematically to identify alternate concepts and physical realizations. Experienced designers apply known techniques in a pragmatic way, responding to schedule and competitive pressures. In addition, designers in the car industry are increasingly reusing past parts or assemblies in order to save time or money. In the academic community a set of top-down theories has evolved that appears adequate for design of simple products but may fall short when faced with really complex things like cars and aircraft. Top-down design theory tends to recommend a divide and conquer approach that leads to highly modular products. Aircraft and cars often contain non-modular elements that combine many functions in one part or subsystem in order to optimize weight, energy, or space. Outsourced items must be self-contained modules for a number of practical reasons. Thus it is rare that a design can be purely top-down, purely modular, or totally optimized. A new kind of top-down approach is needed that preserves the ability to meet customer needs and determine the requirements of lower level systems in a rational way.

3.4.3. Combination of technical and business issues

"Our problems are non-technical." We heard this numerous times during this research. What keeps people from adopting good new techniques or tools? Why does upper management think things are going fine while the people on the floor know better? Why do suppliers appear able to deliver quality but the prime contractor has no way of evaluating the promises? Adding more CAD or CMMs will not solve these problems. People need a better understanding of why they are doing what they are doing and why the things they are building were designed as they were. People need to understand the business case behind the technical tools and know where and why money will be saved. Line workers at one station need to know the problems and needs of the people at the next station down the line who are their customers. The more people know about "why," the better they will be able to do their jobs and help others do theirs.

3.4.4. A new perspective on supply chain design and management

Today's products and processes are so complex that one company can hardly afford to know how to do every step or make every part. Henry Ford vertically integrated his company because there were so few competent suppliers. Today suppliers often have better products or processes than top tier firms, and their strength may be growing in some areas. Thus top tier firms are increasingly dependent either for capacity to meet their needs or for the knowledge to make key parts or subsystems. Supply chain *management* (logistics of delivery) is giving way to supply chain *design*, a conscious effort to structure the dependencies so that the product is designed from the beginning by a partnership of companies each of which knows its role in delivering the KCs. Companies need to be very careful during product development to identify each contact chain by which each KC will be delivered and controlled, then to hand out responsibility for each link in the chain to competent suppliers, and finally to monitor the construction and maintenance of each chain.

3.4.5. The need for design tools that emphasize chains

Today's CAD is so good at permitting design of individual parts and vividly displaying them that designers skip over the integrative and definitional stages of design. Designs thus lack an integrative strategy that can be passed on to individual designers and suppliers of parts and to the assemblers. A top-down approach needs to emphasize the logic of the design before the geometric details are approached. Today's CAD can show parts in the correct relative location and can find gross errors that cause interferences. They can also identify when parts are fully constrained. However, they cannot locate parts by joining them at predetermined assembly points, and they cannot create links of such points abstractly in the form of chains such as the DFC. The whole idea of interfaces and relationships needs to be made a top-level definitional tool in CAD systems.

3.4.6. The need for tools that emphasize communicative power

Because members of IPTs come from widely differing disciplines and backgrounds, any new tools to aid the design process need to have high communicative power. It may even be necessary to sacrifice quantitative detail or accuracy for the time being in favor of wide understandability. During early design, wide ranging understanding is more important and in any event there is often too little detail to permit quantitative analysis anyway. Several of the methods and tools developed or used in this research emphasize communicative power over quantitative accuracy.

3.4.7. The need to augment concept design to focus on product architecture

Concept design is the phase where a product's functional requirements are identified and converted into a plausible set of physical elements in a plausible physical arrangement. This arrangement is called the product's architecture. Architectures can be *integral* or *modular*, depending on how independently the physical elements act in delivering the product's functions. Modularity carries several advantages, including simplicity during design and manufacture. In many products, especially complex ones, there is some advantage to integrality, including efficiency in some dimensions of performance. Most complex products therfore contain a mix of integrality and modularity. Integrality can appear in various ways: sets of parts, sets of people, and sets of organizations whose characteristics or activities affect each other in the process of delivering their required performance.

Along with integrality comes what we call "integration risk," the risk that apparently properly design and made elements will not function as desired when assembled into a system. Integration risk spawns cost and schedule risk. A design team needs a way to both establish the architecture during concept design and to assess each concept's degree of integration risk. Often the team establishes the architecture as a byproduct of other decisions and exits concept design without knowing how much integration risk is built in. This risk then attacks the product later in the design process or during production ramp-up. In this project, tools were devloped to help IPTs to focus on architecture options and assessment of integration risk during concept design.

3.4.8. A vision for Chain-driven product development

In modern products, it is increasingly true that quality is delivered by systems or sets of parts working together. Such systems display an integral character. Examples include ride quality in cars and fuel efficiency in aircraft. Design processes therefore need to focus first on identifying the chains of participants (parts, people, companies) in each of these quality delivery systems. We need better design methods, data models, and customer-supplier practices to encourage product development that focuses on these chains. In a true chain-driven product development process, there will be a chief systems engineer to whom will report chief system engineers for performance, producibility, and supply chain design and management. Each of these three will have colleagues who are members in equal standing on IPTs. A simplified organizational chart of chain-driven product development is given in Figure 3-8.

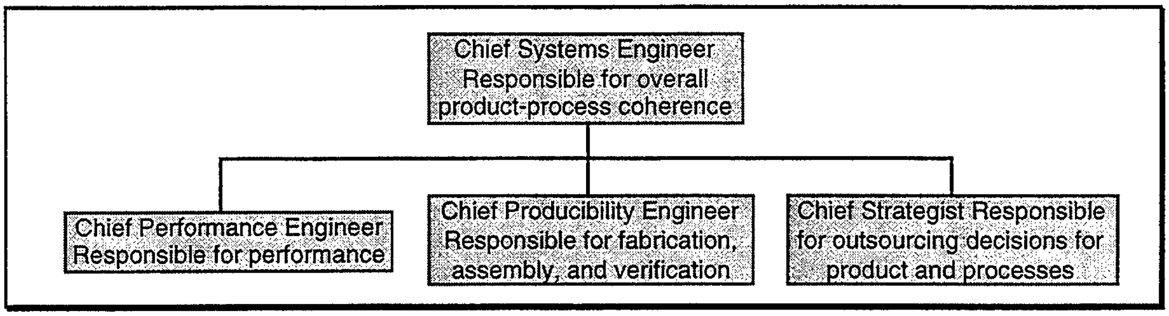

Figure 3-8. Organization Chart for Chain-Driven Product Development

3.5. Section summary

This section of the report presented the context for the research, the web of companies that work together to create complex products, and focused the research on complex mechanical assemblies. The research methodology was explained, the main tools and methods develped were listed, and the main findings were presented. The sections that follow expand on these topics, leading to sections that present details on some of the specific tools and methods developed, with examples of their use.

3.6. References

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4. The Web-Driven Product Development Environment

4.1. The Product Development Process Seen from the Point of View of Assembly

To set the stage for the technical results presented in Sections 5 - 12, we need to describe the environment in which complex products are designed and procured. Since the focus of this research is assemblies, we first describe in Section 4.1 the integrative capability of assemblies and their usefulness as models for how design and procurement of other complex items could be managed. The second topic, treated in Section 4.2, is outsourcing, the act of contracting with other companies to make or even design some of the parts or subassemblies. Depending on the characteristics of these assemblies and the degree of design and manufacturing knowledge retained by the prime contractor, we indicate four different kinds of outsourcing situations which have different promise of success. A summary of a case study from an industrial partner (Section 4.3) is used to illustrate how different companies approach outsourcing and the lessons that can be learned. The third topic, treated in Section 4.4, is the specific management of dimensions and tolerances in the parts and subassemblies, whether they are outsourced or not. The story of Ford Motor Company's Dimensional Control Group is used to illustrate the requirements of this activity.

Our research leads us to conclude that design and management of the supply chain for complex assemblies must be handled very carefully. In particular, the contact chain that traces delivery of Key Characteristics among sets of parts must be mapped onto the supply chain itself, as illustrated in Figure 1-4, so that all interfaces between parts and companies are recognized in advance and fully documented.

4.1.1. Assembly as an integrator

Products are increasingly being made by a "web" of companies, as illustrated in Figure 1-1. The example in Figure 1-4 indicates that some things are outsourced almost down to the last part and fixture. The "moment of truth" occurs at the top of the web when all the outsourced items must come back together and work together. Mechanical assemblies provide excellent examples of the challenges faced by companies in such a process. Integration errors in assemblies are palpable: you can feel them or see them directly. Customers notice them. Product function may be hurt in obvious ways. Thus assemblies and assembly processes are coupled directly to fabrication, vendor control, quality, and market acceptance.

For these reasons, assembly can be used as the focusing issue for achieving integration in web-driven product development. Assembly is the

first time that parts are put together. Before that point they are designed, made, handled, and inspected separately. During and after assembly they are joined, handled, inspected, and must work together. Thus assembly is inherently integrative. One can look back upstream to the design and production process from the point of assembly and see clearly the need to carry out these upstream processes in as integrated a way as possible.

In this section of the report, we will look at two important aspects of web-driven product development that affect final assembly quality: strategic aspects of outsourcing and development of dimensional control plans that include suppliers. To support this discussion and also later discussions of research results, we need to review the concept of integral and modular designs.

4.1.2. Integral and modular designs

When a product is designed, one of the first steps is to list the functions the product must perform and then conceive of various physical embodiments that have a chance of delivering the functions. The conversion of functional requirements into physical elements involves creating the product's "architecture." Product architecture is the scheme by which the functional elements of the product are arranged into physical chunks and by which the chunks interact. [Ulrich and Eppinger] Two main kinds of architecture are integral and modular. In an integral architecture, parts may contribute to many functions, and functions may be delivered by many parts. These parts are likely to have many complex interactions with each other. In a modular product, each part is likely to have one function, functions are likely to be delivered by one or a few parts, and parts are likely to have few interactions with each other. Most products contain a mix of integral and modular features.[4] Figure 4-1 shows integral and modular car bodies.

Integral and modular architectures each have their advantages and disadvantages. Integral is often used when the designers want efficiency in terms of weight, energy consumption, or space occupancy, because interfaces between modules usually require additional material. Integral is often unavoidable, as discussed in Section 5, because product elements have complex interactions even though they appear to be separate. Mechanical assemblies are a prime example of this hidden integrality. Modular designs are appealing because they separate functions as well as the people and organizations responsible for them into manageable chunks that can operate somewhat independently. While the principles of system engineering and

[4] In a bicycle, parts like the wheels, pedals, and chain are modular, because they do one primary thing for one functional purpose, but the frame is integral since it serves many functions: bracing the wheels, anchoring the steering mechanism, and supporting the rider, among others.

product design theory aim for modularity as an ideal, most real products are a mix of integral and modular characteristics and thus require care during design to ensure that the integral portions are accounted for ahead of time.

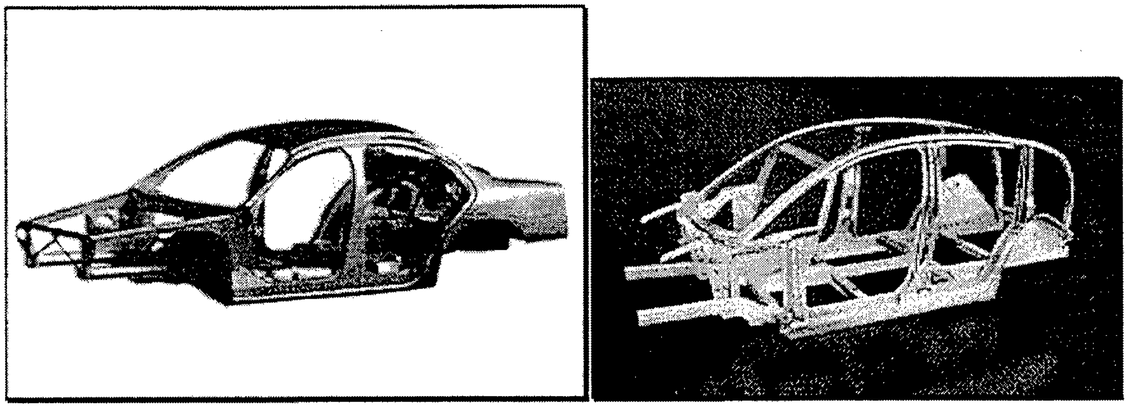

Figure 4-1. An Integral Car Body (left) and a Modular One (right). On the left is a typical steel car body, in which some parts have both interior (i.e., structural) and exterior (i.e., cosmetic) portions. On the right is an aluminum space frame body all of whose parts are interior. The exterior parts are all fastened to the frame and contribute little or nothing to the car's structural integrity.

This point is relevant to the design and function of assemblies. Modular assemblies will get much of their quality from the assembly process itself because each part has only a few features, whereas integral assemblies will get much of their quality from their fabrication processes because each part has many features. In the limit of 100% integrality, such as in large composite aircraft parts, basically all of the quality is attained during fabrication (cutting, layup and cure). However, it is a mistake to assume that just because an assembly has many parts, it is modular. In fact, the parts may have many complex dimensional relationships with each other, all of which must be set up correctly during fabrication and assembly in order that final quality is achieved. In Section 4.2, the success or failure of outsourcing is related to integrality and modularity. In Section 7, we introduce the concept of "integration risk" and show how it can be predicted qualitatively during concept design by carefully mapping the architecture using contact chains. Sources of risk that this method can identify include managerial, organizational, and technical, including issues raised by outsourcing.

4.2. Extent of Outsourcing and Its Effects

Outsourcing decisions are often made on a short term basis by comparing the cost of making an item with the cost of buying it. Usually the costs being compared fail to include many components, such as managing the supplier. As technology advances, many companies find that they cannot be good at everything, and thus find it necessary to outsource regardless of cost. Other

companies outsource for business or even political reasons, such as mandated subcontracting in defense contracts or "offsets" used by commercial aircraft builders to obtain foreign sales.

During this research we had a chance to think about outsourcing [Fine and Whitney] and identified the following issues:

• Outsourcing can create integration risk and management problems if integral items are split up with part going to one supplier and part to another (or part being kept in-house)

• Outsourcing can create dangerous dependency for critical product or process technologies

• Only certain combinations of type of dependency and degree of modularity are appropriate for outsourcing; others can cause serious managerial or strategic problems

• Companies that outsource face the problem of monitoring suppliers who may have skills that the outsourcing company no longer has; this makes it difficult to formulate competent specifications for the outsourced item and to determine if the supplier has met the specification

4.2.1. Different kinds of dependency

Dependency on a supplier can be trivial or total. We categorize dependency into two main types:

- dependent for capacity, and

- dependent for knowledge

Dependency for capacity simply means that a company needs more of an item than it can conveniently provide. It knows how to make the item and finds a second source to augment its needs. Dependency for knowledge is totally different, because the company no longer knows how to make the item and must obtain it outside. In the spirit of agility, many companies voluntarily opt for being dependent for knowledge. One can wonder at the long term wisdom of such a policy.

4.2.2. Different kinds of oursourcability

The easiest things to outsource are those that are easily separated from the rest of the product physically and functionally. Completely modular products can in principle be outsourced down to the last part. Simple circuit boards are an example. Not only can a properly designed board be outsourced,

but the common circuit elements on the board can be further outsourced. It is more difficult to outsource aircraft fuselage panels, however. These are large and join many other panels in many places. A large number of different dimensional relationships must be satisfied at the same time in order to create a strong and attractive assembly.

4.2.3. The dependency-outsourcability matrix

In Figure 4-2 we have combined the extreme possibilities of integral and modular (decomposable) with the two kinds of dependency to create four situations. Each situation is more or less desirable for a company considering outsourcing.

	DEPENDENT FOR KNOWLEDGE	DEPENDENT FOR CAPACITY
OUTSOURCED ITEM IS DECOMPOSABLE	**A POTENTIAL OUTSOURCING TRAP** YOUR PARTNERS COULD SUPPLANT YOU. THEY HAVE AS MUCH OR MORE KNOWLEDGE AND CAN OBTAIN THE SAME ELEMENTS YOU CAN.	**BEST OUTSOURCING OPPORTUNITY** YOU UNDERSTAND IT, YOU CAN PLUG IT INTO YOUR PROCESS OR PRODUCT, AND IT PROBABLY CAN BE OBTAINED FROM SEVERAL SOURCES. IT PROBABLY DOES NOT REPRESENT COMPETITIVE ADVANTAGE IN AND OF ITSELF. BUYING IT MEANS YOU SAVE ATTENTION TO PUT INTO AREAS WHERE YOU HAVE COMPETITIVE ADVANTAGE, SUCH AS INTEGRATING OTHER THINGS
OUTSOURCED ITEM IS INTEGRAL	**WORST OUTSOURCING SITUATION** YOU DON'T UNDERSTAND WHAT YOU ARE BUYING OR HOW TO INTEGRATE IT. THE RESULT COULD BE FAILURE SINCE YOU WILL SPEND SO MUCH TIME ON REWORK OR RETHINKING.	**CAN LIVE WITH OUTSOURCING** YOU KNOW HOW TO INTEGRATE THE ITEM SO YOU MAY RETAIN COMPETITIVE ADVANTAGE EVEN IF OTHERS HAVE ACCESS TO THE SAME ITEM.

Figure 4-2. The Matrix of Dependency and Outsourcability.

In the upper right is the best situation. Here, a company understands the item to be outsourced, and it is easily defined by simple specifications of a few interfaces. It is easy to tell if the supplier has done a proper job. By contrast, the situation at the lower left is the most dangerous. Here the company is totally dependent and may not have enough skill to manage the multiple interfaces that an integral item presents, especially when it no longer knows

how to make that item and may have created an imperfect specification as a result. An imperfect spec will generate integration problems of its own, making the final assembly even more difficult.

Section 7 of this report elaborates on this classification of outsourcing situations and includes risk assessment of outsourcing in a broader evaluation of integration risk.

4.3. Mechanical Assemblies as Indicators of Supply Chain Performance

In his study of "black box parts," Fujimoto found that Japanese car manufacturers gradually converted outsourced modular parts like steering wheels from build-to-print (so called white box) to build-to-spec (black box) over a period of 20 years by gradually improving the capabilities of the suppliers. However, parts like rubber door seals never advanced beyond the white box category even after 20 years. [Fujimoto] This example indicates that the distinction between integral and modular is important in defining the limits of outsourcability: door seals depend for their performance on the dimensions of many other parts and thus must be controlled in detail by the prime. Steering wheels attach with a bolt and an electric plug (until the era of air bags) and are relatively easy to decompose, describe in a spec, and outsource completely.

A more striking example is provided by research work in this project at General Motors Delphi Saginaw Division. MIT staff and students performed a detailed analysis of how one product, a half shaft for front wheel drive cars, is made. Delphi is one of the world's leaders in half shaft design and manufacture, and its customers include most of the world's car companies. Figure 4-3 shows a half shaft. These items transmit large amounts of power and are critical safety items. Their flexible joints must be made extremely carefully with close clearances and tight tolerances.

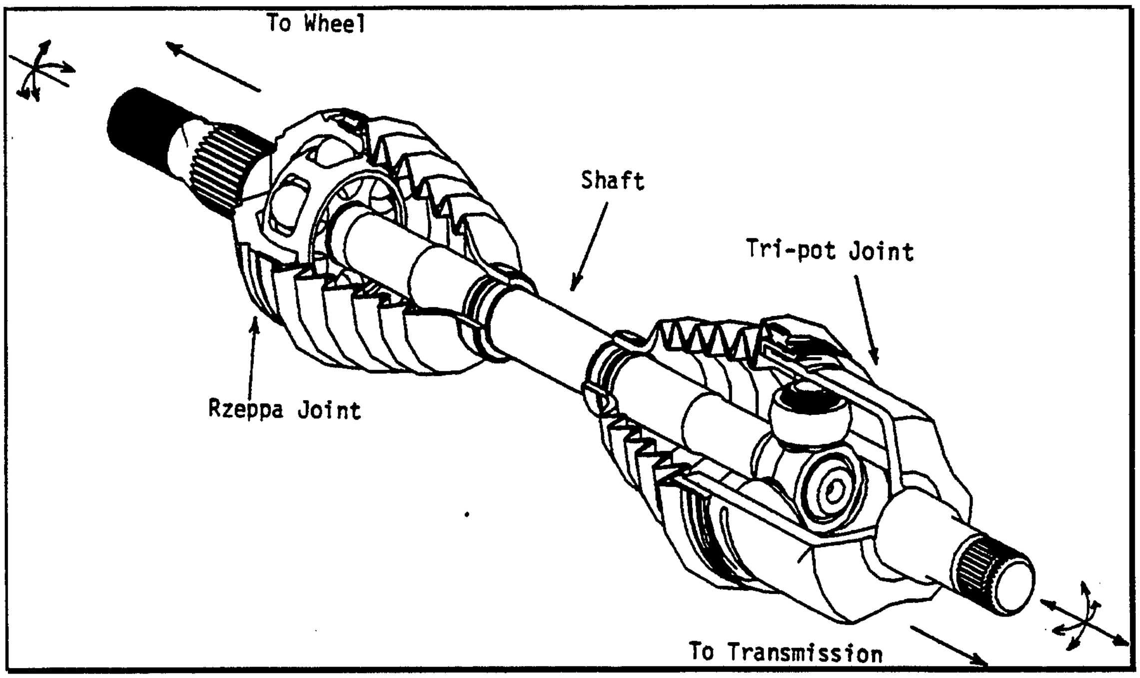

Figure 4-3. A Typical Automotive Half Shaft

Our research showed that different car companies specify their half shafts to Delphi rather differently. Some give minimal engineering specifications, such as length and maximum torque. Toyota, however, provides detailed specifications, including a design verification test to determine the first mode transverse vibration frequency. Such a specification has nothing to do with torque carrying capacity, but rather with noise, vibration, and harshness (NVH). Clearly, Toyota considers the half shaft not merely a torque carrier but as a member of the NVH system. The half shaft thus is not a module but an integral item. Figure 4-4 shows the half shaft as a member of the NVH system.

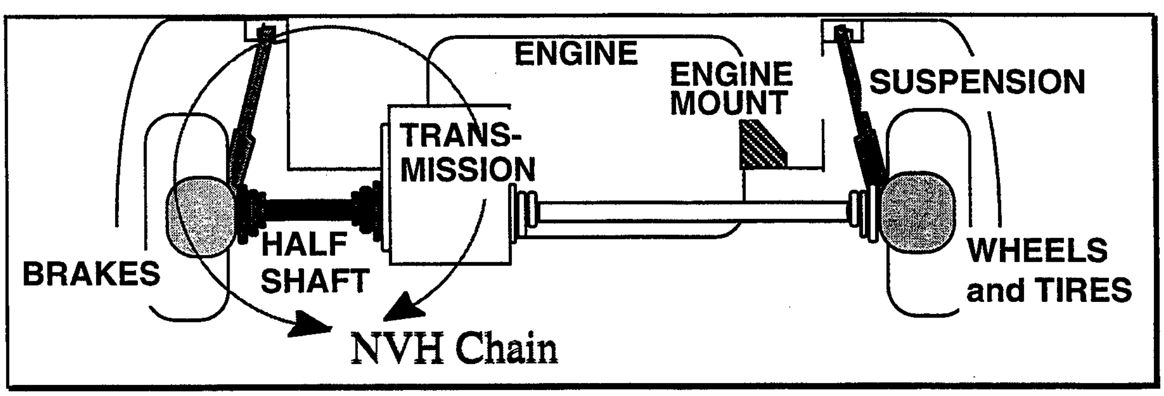

Figure 4-4 . Illustrating the Role of the Half Shaft in the NVH System. The system includes engine and mounts, transmission, half shaft, wheels and tires, suspension, and body.

Why then does Toyota feel comfortable outsourcing it? MIT researchers asked Delphi engineers if Toyota goes so far in its specifications as to dictate tolerances. "They would never dream of telling us what tolerances to use. But, if we begin to fail the qualification tests, then they start to get 'helpful.' They are the best in the world and they want us to be, too. They gently nudge us toward the design they knew all along we should have used."[5] It turns out that Toyota makes some of its own half shafts. This indicates that Toyota is dependent for capacity and this explains why it can comfortably outsource an item it obviously considers integral.

4.4. Description of Ford's Dimensional Control Program

The body parts of cars provide a useful illustration of management of dimensions. These parts are complex and difficult to make. Customers pay careful attention to how they fit and whether they permit water leaks or wind noise. Since around 1990 US car firms have greatly improved their control of assembly dimensions, flowing down those dimensions to the parts. Prior to this time it appears that the parts were designed individually without a lot of consideration for how they would be assembled. Assembly process design was considered to be a job for tooling engineers and was addressed much later in the design process.

According to a case study by MIT [Lee], Ford began to pay closer attention to dimensional control after the famous Toyota television commercial that showed a ball bearing rolling along a hood-fender gap. It required the authority and initiative of a Vice President to start the process. At first it was thought that the solution lay in coordinating the calibration of all gages and fixtures, but one employee in the body tooling department determined that the solution lay in a top-down design process that assigned dimensions, tolerances, and "locators" systematically. Locators are features on the parts by which they attach to the fixtures or other parts. Starting with methods and terminology borrowed from Mazda, Ford developed a standard set of locator designs and methods for applying them. Figure 4-5 is an example part together with many of the symbols. Ford personnel also contacted McDonnell Douglas personnel and learned advanced methods of calibrating fixtures using theodolites and methods of training and qualifying theodolite operators.

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[5]Paraphrase of interview with Jerry Eaton, Jan 19, 1995.

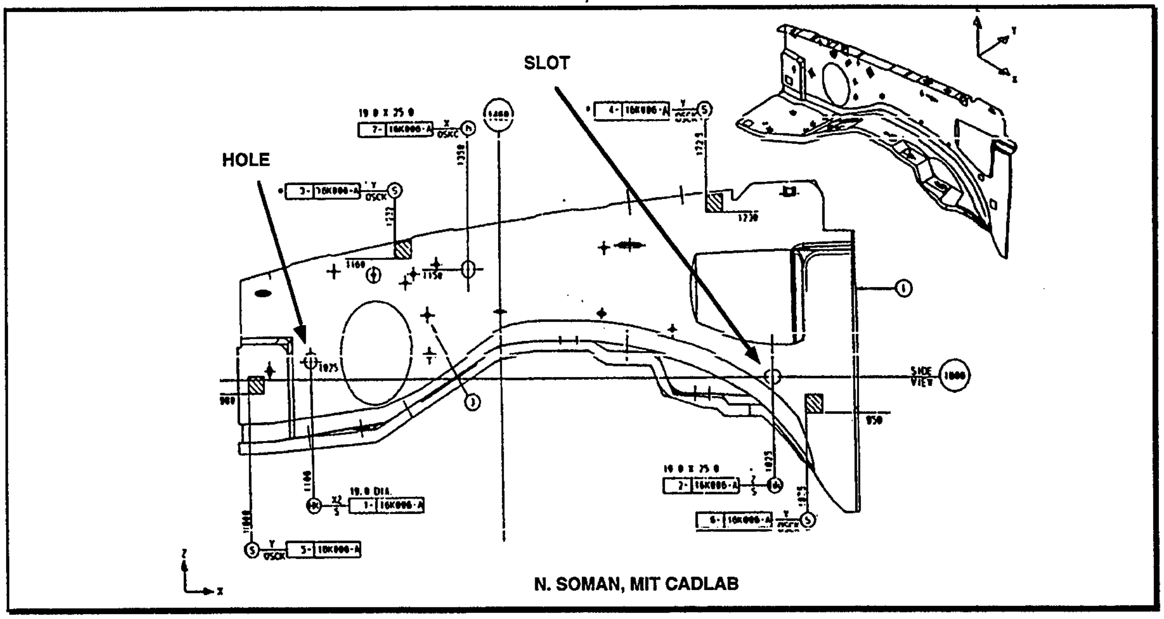

Figure 4-5. Locator Drawing for an Inner Fender Panel. Locators are highlighted with leaders and boxes containing symbols like H (hole) and S(slot).

Ford's locator "vocabulary" includes names of features used for locating, such as hole, slot, and edge, as well as nuances such as "temporary" to indicate that a locator substitution has occured at one station because the main locator is temporarily obscured, and "transferred" to indicate that datum reference has been permanently transferred because the original locator is permanently obscured.

It is typical that following body design, the development of locator strategy, tooling design, stamping die design, and assembly line design take a year of team effort involving the respective Ford and vendor personnel. A set of books about a foot thick containing drawings like that in Figure 4-5 is the result. This set of books becomes the bible for all subsequent design of individual parts, dies, jigs, assembly fixtures, and check fixtures. Section 9 of this report describes how this information is used on the factory floor to solve assembly problems during production launch. Except for CAD tools adapted to display locators, and the use of VSA (commercial software for tolerance analysis), the design of locator schemes is carried out manually by experts.

Ford personnel understood that the task of improving dimensional control required organizational changes. Ford established the Dimensional Control Group (DCG) in the Body and Assembly Operations (B&AO) department in 1991. B&AO is responsible for designing sheet metal stamping and assembly lines as well as for contracting for the construction of those lines, supervision of assembly launch, and solution of body assembly problems. By placing the DCG in B&AO, Ford effectively joined dimensional

control analysis with control of tooling to achieve dimensional control. Furthermore, Ford provided that the DCG would have design review authority over all body designs. Ford thus achieved good integration of all the elements necessary for managing assembly quality: design, assembly tooling, and assembly line design. Section 9 of this report describes how this information is used for corrective action during production ramp-up.

Our research at aircraft companies indicates that few have achieved similar integration. MIT researchers visited most domestic and foreign manufacturers of large commercial aircraft and did not find evidence of either a company-wide policy that joined tooling and assembly departments into one organization or strongly involved assembly and tooling considerations into an up-front dimensional control plan. At one company, an engineer said "The vendors make the parts using whatever dimensional datums suit their production processes. We have to spend a long time adjusting them to make the assemblies go together." Only at McDonnell Douglas [Behan] among aircraft companies is there evidence that good dimensional control occurs.

When Boeing designed the 777, unprecedented efforts were made to involve suppliers and production people in the design process, and there is strong evidence that this paid off handsomely in reduced assembly problems. It is not clear, however, that a systematic top-down process was followed.[6] More recently [Muske], Boeing has studied such a process for an advanced 747 program. Personal contacts with the author indicate that no computer-based methods are currently available to support such a process, which relies instead on experienced people. The methods described in Section 6 of this report may prove helpful.

Ford personnel are also aware of the degree of complexity of assemblies and the need to prioritize the tolerances and KCs. For example, car doors are made of an inner panel and an outer panel. The outer should maintain a constant gap with the surrounding body for appearance purposes. The inner should maintain a constant gap with respect to the same body area for leak and noise purposes. Since inner and outer are joined as a subassembly, there will be errors, and it is impossible to perfectly align the outer and the inner to the body simultaneously. Ford personnel are clear that the inner should be set correctly and the outer allowed to fall as it may, because the customer will notice leaks and noise every day and will be unhappy.

Some of our aircraft partners appear to want to achieve every KC to the same level of tolerances. When large structures are joined, many features are supposed to align. Strictly speaking, such an assembly action has only 6

[6] MIT staff and students studied 777 fuselage final assembly and first tier supplier practices. Portions of the findints appear in [Mantripragada].

degrees of freedom for making alignment adjustments. Typically, the number of KCs to be achieved during such a mate presents far more than 6. Instead of prioritizing, the assemblers apply force in an attempt to align the other KCs. This can be done up to the point where too much energy is locked into the structure, above which flight load margins are eroded or stress-induced corrosion might occur.

The common approach to such problems is to tighten all the tolerances. In fact the correct approach is to maintain the tolerances on the highest priority KCs and mate them first, using up the first 6 degrees of freedom in the process, while the other KCs should be given looser tolerances consistent with the fact that they must be allowed to fall where they may once the first ones are mated. Otherwise, the assembly will be over-constrained and energy will be stored in it. If this approach does not succeed in permitting important KCs to be achieved to the desired tolerance, then a different assembly sequence must be adopted that mates the degrees of freedom in some different way. Section 8 of this report presents a theory of top-down design of assemblies that describes this idea in detail. Clearly, a different assembly sequence will probably create different modules and subassemblies. The dimensional pros and cons of different modularizations can in fact be studied during concept design, when such ideas are considered and frozen, usually without understanding their effect on assembly. Section 7 of this report presents a theory to address this issue.

Nowhere in the aircraft industry did we observe the level of sophistication that is evident in the car industy. The elements observed at Ford are:

- recognition that several key organizations (assembly line design, tooling design, tooling outsourcing management, assembly line installation, and production launch) must report to the same high level manager

- recognition that a separate dimensional control group can provide a valuable skill center for anchoring the process

- a mandate that dimensional control be part of the design review process for assemblies

- development of computer tools for describing locators and provision of computerized libraries of standard locator designs

- integration of tolerance analysis software into locator design methods [Sweder and Pollock]

- adoption of KC priorities

• realization that management attention and energy must be devoted to maintaining the dimensional control plan once it is adopted so that the many people and suppliers involved do not inadvertantly change something and upset the plan[7]

The car industry has learned a great deal about dimensional control, design of assemblies, KCs, and outsourcing of assemblies. The aircraft industry appears to be learning the same lessons on about a 6 to 8 year time delay. This delay could be shortened if more cross benchmarking and learning between the two industries took place.

4.5. Section summary

This section provided background information on topics that are further developed later in this report. Assemblies were identified as models of integrative design challenges. Integral and modular designs were defined, and the advantages of each were listed. The pitfalls of integral designs were identified in terms of assembly, or integration, risk as well as outsourcing risk.

Two industrial examples of outsourced assemblies were given, half shafts and car bodies, and Ford's methods of managing this process were described. While aircraft companies face similar problems, they appear to lag the car industry in applying best practices.

The following sections of the report describe in detail several research activities and new tools or methods that address the issues raised in this section.

4.6. References

[Fine and Whitney] "Is the Make-Buy Decision a Core Competence?" MIT CTPID working paper, May, 1996.

[Fujimoto] Fujimoto, T., "The History of the Black Box Parts Method in the Japanese Car Industry," University of Tokyo Department of Economics Working Paper 94-01.

[Sweder and Pollock] Sweder, T. A. and Pollock, J., "Full Vehicle Variability Modeling," SAE Paper 942334.

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[7] As quoted above: "First you have to make the plan and then you have to ride herd on the plan."

[Lee] Lee, Don, "Report on Key Characteristics Development in the Auto and Aircraft Industries," working paper, MIT Fast and Flexible Manufacturing Project, December, 1996.

[Behan] Behan, W. M., "Process Capability Methodology for Integrated Product Development," Wright Laboratory report WL-TR-95-8016, May 1995

[Muske] Muske, Scott, "Application of Dimensional Management of 747 Fuselage," presented at World Aviation Congress and Exposition of SAE, Anaheim CA 1997

[Ulrich and Eppinger] Ulrich, K. and Eppinger, S., Product Design and Development, New York: McGraw-Hill, 1995

5. Key Characteristics[8]

5.1. Introduction

Design and Manufacturing firms are under significant pressure to increase product complexity, reduce design cycle times, decrease cost, and improve quality. These pressures often result in missed cost, quality, and delivery time targets during product development. These failures, however, can be avoided by early identification and mitigation of potential problems.

A lead article in the Wall Street Journal [Cole] recently reported that Boeing would produce 20% more planes in the following year. The article also pointed out that it is critical to Boeing's profitability that the cost of manufacturing be kept low. To do this, process steps that add no value must be removed. One of the largest avoidable costs in aircraft is rework due to variation. In the case of aircraft, rework can include processes such as tapered shims, trimming of panels, and refitting of parts. Other costs of variation include quality losses, scrap, and repair. This problem is not unique to Boeing. Cost incurred due to variation is a common problem in many product development and manufacturing organizations.

In order to develop low cost products it is necessary to predict and mitigate the effect of variation early. For example, Ford "Windstar" vehicle development used assembly variation modeling throughout product development. Ford estimated up-front attention to variation saved between $5 and $10 million dollars in downstream rework costs. [Sweder] Variation can be reduced in the design stage by product and manufacturing changes. In addition, variation can be controlled during production through variation reduction plans, SPC, or inspection.

Variation management can be very complex and expensive. Even small products can take multiple gigabytes of memory for CAD models and this can translate into millions of dimensions. One major challenges during design is to identify a small set of critical parameters that significantly affect customer requirements and focus product development and quality effort on these.

To solve the question of what small manageable set of characteristics are most sensitive to variation, A variety of manufacturing organizations have explored using "Key Characteristics" (KC) method. KCs—also termed critical parameter management, key product characteristics, key quality characteristics—are those features whose variation has significant impact on product requirements. KC methods define the process by which KCs are identified, managed, tracked, and improved. Organizations using KCs include

[8] This Section was written by Prof Anna Thornton, MIT Department of Mechanical Engineering

Boeing, GM, Ford, Chrysler, Xerox, Kodak, Northrop Grumman, McDonnell Douglas, and ITT.

During the course of the Agile Manufacturing Project, the author and her students spent significant time with several design and manufacturing organizations discussing KC usage. Every organization expressed the need to identify very early in design processes what system level Key Characteristics are most likely to not be achieved during production due to variation. Early attention to variation is important because design changes early in the design process are less expensive than improvements made during manufacture.

This report is a summary of work completed over the course of the Agile Project. Agile funding was combined with the funding from the Lean Aerospace Initiative, Leaders for Manufacturing, the NSF-MIT Center for Innovation and Product Development and a career award from NSF.

This report is broken into four sections. The first presents the ideal KC method. The second is a summary of the current state of industry. The third section contains a summary of three efforts in the KC Group. The fourth section contains results and recommendations for future work.

5.2. Ideal KC Methods

This section provides a set of terminology and a proposed ideal method for KC management. This set of definitions and methods provides the baseline against which the current industry practices and research is measured. This ideal method has been developed through observation of many organizations' processes and it represents accumulated best practices.

5.2.1.1. Definitions

KC methodologies include tools and processes to identify KCs, to assess their impact on product quality, and to reduce variation impact. Central to KC methods is the use of *Key Characteristic Flowdown*.

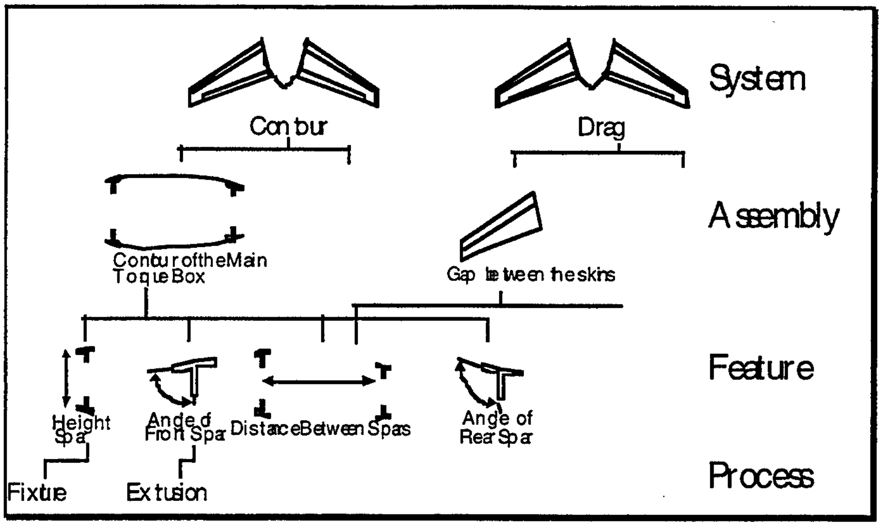

Figure 5-1: Key Characteristic Flowdown

Figure 5-1 shows a schematic of an example KC flowdown. KCs are described in a hierarchical tree structure (a KC flowdown for contour and drag characteristics of an aircraft wing). At the top of the tree are system KCs -- product requirements set by the organization. System KCs are flowed into sub-system and feature-level KCs and each assembly step is represented by a parent/child relationship. The sub-system KCs are sub-assembly features that are created by an intermediate assembly or manufacturing processes. The feature-level KCs are those created by manufacturing processes or delivered by a supplier. System and feature KCs have many layers between them. The KC flowdown is made more complex because sub-system and feature KCs often contribute to more than one system KC. For example, the distance between the two spars affects the gap between the skins as well as the contour.

Not all KC flowdowns are purely dimensional. Different industries have different KC flowdown types. Figure 5-2 shows hierarchies for three industries. For example, semi-conductor industries' final system performance is functionally based. The function is based on its electrical performance, which in turn, is based on the mechanical properties of the layers in the chip. Similarly, a camera function, such as shutter performance, is based on physics of springs and actuators. These, in turn, are driven by dimensional properties of parts.

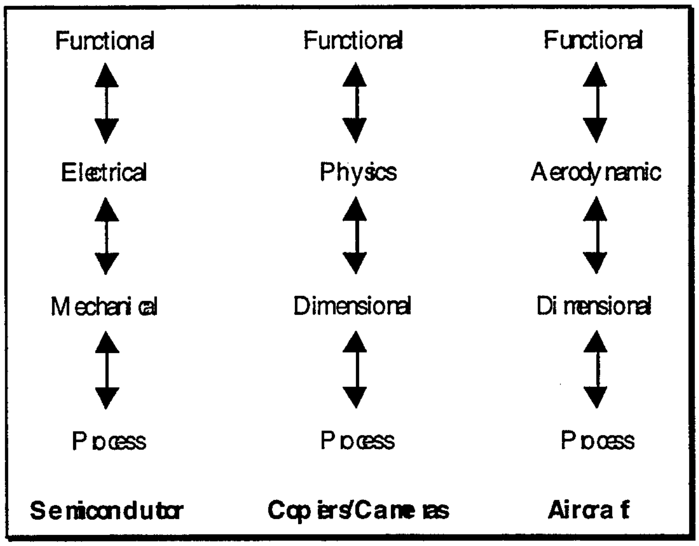

Figure 5-2: Typical Flowdown Characteristics for Various Industries

5.2.1.2. Ideal KC Process

Figure 5-3 shows a representation of the ideal Variation Risk Management (VRM) process. First, system requirements that may be affected by process variation are identified. In addition, allowable latitude should also be specified. Latitude is the maximum amount of variation that can be tolerated by a customer. This is also referred to as the tolerance.

For aircraft, system requirements can include maximum wing alignment variation, maximum body alignment variation, and maximum steps and gaps between skin panels. Copier requirements can include paper handing and print quality. The second step involves flowing requirements down feature level to generate a KC flowdown (Figure 5-1). This process is done in parallel with the design process. After the flowdown is completed, manufacturing process capability for the features is collected. The variation in the system requirements is then calculated by *flowing up* process capability. Process capability flow-up can be done using a variety of tools including back-of-the-envelope calculations, such as root sum squared, tolerance stack-ups, or computational methods such as Variation Systems Analysis (VSA). The predicted performance is then compared to allowable system latitude.

If unacceptable variation is predicted, variation mitigation strategies are employed. Five strategies are used in industry (these will be discussed later in detail): design changes, process changes, process improvement, SPC, and inspection. Based on the strategy cost and effectiveness, the most appropriate method is selected and executed. The process in Figure 5-3 is iterated until the design is complete or the design schedule dictates that it must be released.

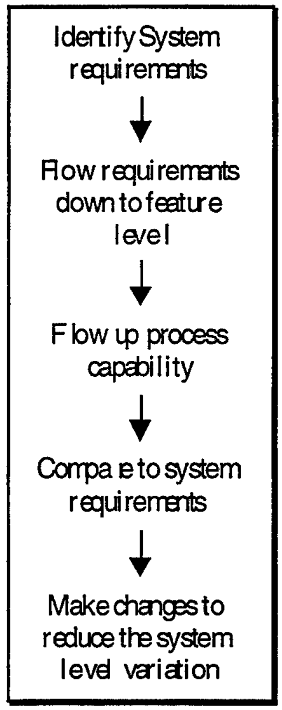

Figure 5-3: Ideal Process

This ideal process is made more complex because early in the design process there is uncertainty about system requirements, flowdown, and process capability. The cost of a product is designed during the early design stages in common wisdom. In addition, robustness changes to the design are most cheaply made in the early design stages.

This rule is understood by most engineers. However, interestingly, most design teams do not make effective use of design flexibility in early stages. It is the author's hypothesis that this inability is caused by uncertainty in design.

Early in the design stages, when major choices of design concepts, tooling, and assembly are made, there is very little detailed knowledge about variation and its impact on the final product quality. Changes to the design concept may impact performance and/or design schedules. In addition, the effectiveness of the design changes may not be clearly quantifiable. The author hypothesizes that it is uncertainty about the impact of changes that drives designers to postpone implementing variation mitigation strategies.

One method to reduce this problem is to increase the level of modeling detail early in the design process. However, this requires designers to make decisions about the design and invest time into those details. Consequently, the design becomes less flexible and multiple design concepts cannot be evaluated quickly.

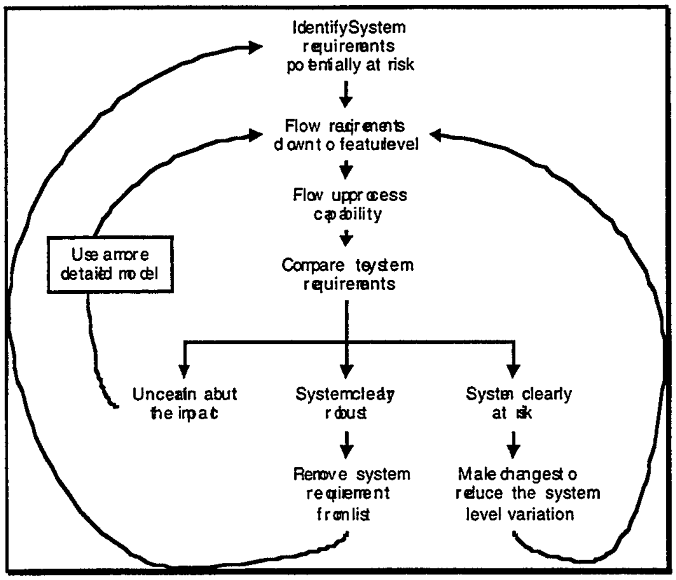

Figure 5-4: Level of Analysis Detail as a Function of Time

Figure 5-4 shows a refined approach to VRM that addresses uncertainty in the analysis and data. The first four steps are the same as Figure 5-3. However, in addition to process capability analysis, uncertainty in predicted values is also quantified. When the fourth step is reached, the designer is faced with three possible cases. In the first case, if the impact of uncertainty is too great, a more detailed model with more accurate data should be used. In the second case, if the system is clearly robust to predicted variation, that system requirement is removed from the current list. In the third case, if the system is clearly not robust, changes to design or manufacturing process must be made. Figure 5-5 shows a representation of the iterative analysis process. Early in the design process, variation analysis is applied across the entire product but using rougher models. With time, accuracy of models is increased but is applied to a smaller set of potential problems.

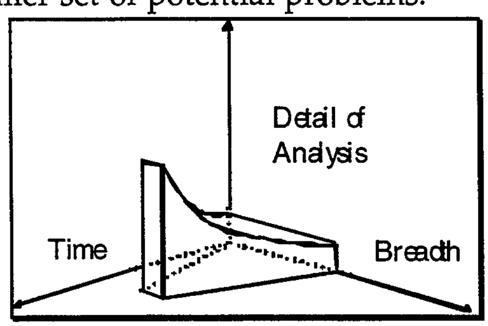

Figure 5-5: Detail vs. Breadth

In general, KC process can be divided into three steps. First is product KC identification. The second is analysis of KCs to quantify risk of a failure and uncertainty associated with the analysis. The third are processes used to

mitigate problems through design changes, process changes, or extra control in the manufacturing environment.

The next section reviews the current state of industry as observed by the author and her research group.

5.3. State of Industry Implementations

Pockets of excellence exist in applications of KC. However, current tools and methods have many shortcomings. Shortcomings in identification, assessment, and mitigation of risk are summarized in the following sections.

5.3.1. Identification

There is often a good understanding of system-level parameters that are sensitive to variation. For example, at Boeing, a drawing captures system-level KCs. This drawing includes such features as the wing incidence angle, wing contour, and steps and gaps between aircraft skin panels.

For most of companies, the key barrier that we observed was the translation of these system requirements into sub-system, feature, and process key characteristics in order to generate a KC flowdown. Proper generation of a KC flowdown is critical to both assessment of risk as well as selection of an effective mitigation strategy. The inability to create KC flowdowns is a result of several factors:

- **Organizational.** Most companies break their products down into individual parts designed by separate groups. Consequently, individuals identify features on their parts that may impact system level requirements but they are not flowed through intermediate layers.

- **Documentation.** Most companies do not have effective documentation of their KC flowdown. In most cases, KCs are designated on drawings but the drawings do not capture the hierarchical relationships shown in Figure 5-2.

- **Training and incentives.** Training manuals discuss use of KC flowdowns but do not explain it in any detail. In addition, although engineers understand the importance of KC flowdowns, they are not provided time in the design schedule to effectively create flowdowns.

- **Non-Product KCs.** Often KCs are limited to parts that make up the final product. However, in many cases, significant variation is introduced by fixtures, processes, in-process adjustment, etc. These are often not explicitly captured or modeled in KC documentation.

5.3.2. Assessment

Once KCs are identified, the level of risk should be assessed. As will be shown later sections, this step is the least well done.

Risk is made up of two factors: chance of failure and cost of failure. All features are placed in one of four categories defined by high and low chances of failure and high and low cost of failures Figure 5-6. In case (1) where the chance of failure and cost of failure is low, there is no further action needed. In case (4), where it is known that the chance of failure and cost of failure is high, effort can go directly to risk mitigation step where either cost or chance of failure can be reduced to an acceptable level. In cases (2) and (3), it is not clear if effort is needed to reduce risk. In both of these cases, a more detailed and quantitative understanding of costs is required.

		Chance of Failure	
		Low	*high*
Cost of Failure	*low*	(1) No risk	(2) Risk Assessment
	high	(3) Risk Assessment	(4) Risk Mitigation

Figure 5-6: Risk Management Strategy

Taguchi cost/loss functions are one way in which variation impact on cost can be quantified. The problem with Taguchi cost functions is that cost information is available at the product system level but variation information is available at the feature level (i.e., at the level of manufacturing process). Tools are needed to map process variability up to the system level. Methods to map cost down the flowdown to the feature level are often arbitrary and can lead to erroneous results.

In general, three key information sources are required to make an accurate variation impact assessment. First, there must be a good product *model*. As stated in the previous paragraph, models depend on an understanding of system to feature-level relationships. Second, there must be a good understanding of process capability of both internal producers as well as suppliers. Third, there should be a good understanding of cost implications of variation.

5.3.2.1. Models

A range of models is used to determine the system level effect of feature variation on system KCs. Companies use three model types to quantify variation effects: back-of-the-envelope calculations such as root-sum-squared (RSS), Design of Experiments (DOE), and Variation Systems Analysis (VSA).

Back-of-the-envelope calculations are used to do rough estimates of the size of variation. These are typically done by individual engineers and are maintained in Excel files or other private documents. The problem with these models is that they are not available to other design team members. In addition, they are not updated automatically.

Design of Experiments (DOE) are used when prototype hardware exists that can be analyzed using Taguchi methods. DOE is very effective when hardware exists. However, it is not available in early design stages when there is no hardware.

VSA models are used by a range of companies to predict variation effects. They require a detailed geometric model as well as a model of assembly processes. These are very effective at modeling variation after detail design is completed. However, industry has had a mixed reaction the software. VSA is accepted as a valuable tool but it is also viewed a time and resource sink.

There is also a gap in current modeling techniques. Figure 5-5 showed that a first-order analysis method is needed early in the design process to assess variation risk. Currently, the only method available are hand-carved models. A set of tools to systematically evaluate risk is required.

5.3.2.2. Process Capability

Knowing process capability is critical in accurately assessing variation risk. If there is little or no knowledge of process capability, it can be very difficult to accurately predict where the product is likely to be at risk of low quality.

To address these problems, companies have implemented a range of process capability databases. Two problems with current implementations exist. First, process capability databases are, in most cases, limited to internal processes. Second, even when process capability is captured, design does not use it in their assessments. This is believed to be a function of several factors including the difficulty in using databases, inaccuracy of data, and a lack of deliverables in the design process to encourage its use.

5.3.2.3. Cost

Cost is the least well understood of the three data sets. There is a systemic lack of data about costs. Two cost systems must be put into VRM processes to enable the most effective prioritization and mitigation strategy. The first is a quantitative understanding of variation cost. Second, and even less well understood, the cost of variation reduction and variation mitigation strategies.

5.3.3. Mitigation

There are various variation risk mitigation strategies. They include design changes to make the system more robust to existing variation; process improvement or changes to reduce variation introduced into the system; process monitoring to ensure that degradation and change in process capability will not affect final product quality; and inspection to sort, repair, or scrap parts that do not conform to quality standards.

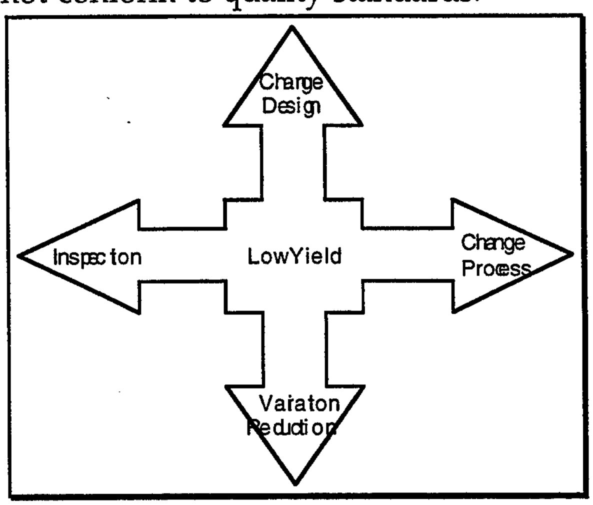

Figure 5-7: Methods to Increase Yield

Figure 5-7 shows four options for variation risk mitigation. Each has different non-recurring and recurring costs. In addition, there may be strategic reasons for selecting one approach over another. Table 1 shows a summary of the four approaches.

•**Design changes** can improve yield for the product life but can sacrifice performance. In addition, they can be expensive if performed late in the process. However, subsequent products can not use design improvements.

•**Process change**, the use of an alternate manufacturing process, can reduce recurring yield costs. Variation reduction is often balanced by increased recurring costs, (cost of producing each part is higher) as well as a

non-recurring cost (cost of capital equipment). However, capital equipment can be used on multiple product lines spreading out costs.

•**Improving existing processes** requires non-recurring resources to implement improvements but results of Variation Reduction (VR) can reduce recurring costs. However, variation is limited by the inherent properties of a process (a chain saw will never cut with a mm precision)

•**Inspection** removes parts whose characteristics are out of specification. Inspection requires minimal non-recurring costs for (e.g., gauges) but recurring costs for measurement, overhead, scrap and rework can be quite high. Thus, this approach has minimal long-term benefits.

No single approach is superior in every case. Each approach has a non-recurring cost required to implement the approach: process change requires capital expenditure and a design change requires drawing changes, retooling and engineering analysis. In addition, each approach is limited in the yield improvements it can affect. As will be shown later, each approach follows the rule of diminishing marginal returns: at some point, more investment in an approach will have no impact on product quality. The appropriateness of an approach is a function of its cost effectiveness: the balance between non-recurring costs and diminishing benefits. For example, for a marginal risk problem (i.e., a high probability of a low cost failure), a design change may not be cost effective and VR may be more appropriate. On the other hand, VR may not reduce cost enough when there is both a high probability and a high cost of failure. In this case, investment in a redesign is more appropriate.

A given yield problem may be most efficiently addressed by one approaches or a combination of several. Ideally, when a variation problem is found, the four approaches should be simultaneously evaluated, and the most cost-effective approach selected. However, current industry practice is far from ideal.

Table 2: Summary of Cost Impact of Changes

	Yield Improvement	*Recurring Costs*	*Non-recurring Costs*	*Strategic Impact*
Design Change	High	None	High-Medium	High
Process Change	High-Medium	None	High-Medium	High
Variation Reduction	Medium-Low	Low	Medium	Medium
Inspection	Medium-Low	MediumLow	Low	Low

It is the author's observation that the inability to make these tradeoffs is due to two problems. First, organizational barriers exist that prevent simultaneous evaluation of the four approaches. Experts in each approach tend to reside in different functional organizations. There are robustness

experts in design, process experts in manufacturing, inspection experts in quality, and process improvement experts in variation reduction groups. Despite a surge Integrated Product Teams (IPTs) in the 1990's, the author has observed that the four functional groups do not work well together. This is consistent with Ancona and Caldwell's observation that "conflicts that inevitably exist between functions that get brought into a cross-functional team and [this] may interfere with defining goals and priorities." Second, even when a team is formed and works well together, it is hard for groups to compare relative cost impacts and benefits of the approaches because few standardized cost models exist.

Industries are very good at implementation of the four strategies. We have found that robustness and SPC are well-understood concepts. Industries want to reduce inspection processes and move to process validation as a way of controlling quality. What they are not capable of doing well is selecting the most appropriate strategy based on a quantitative assessment.

5.3.4. Summary

In summary, three essential barriers have been identified in current KC methodologies:

•Methods/tools to capture the KC flowdown,

•Models that can be used in early design stages that predict

•System variation, and

•Prediction uncertainty, and

•Methods to systematically evaluate and select the most effective mitigation strategy.

5.4. Research Activities

The activities of the MIT KC group are divided into three areas: KC conferences, KC methods, and KC Tools. The KC conference series is an annual conference that brings together practitioners in the area of KCs and Variation Risk Management to discuss and work on common problems. The second area focuses on understanding current KC methods, best practices, and codifying the field. There is a variety of work in this area; however, this document will review one result – the KC Maturity Model. The third area focuses on developing quantitative tools and methods to address essential barriers summarized in Section Summary.

5.4.1. KC Conferences

Two conferences have been held in the last two Januarys. These conferences had the goal of bringing together a variety of industries to share learning and best practices.

NASA Kennedy Space Center hosted the second annual Key Characteristics Symposium on January 21, 22, and 23. The conference series is organized and facilitated by Anna Thornton, an Assistant Professor in the Mechanical Engineering Department at the Massachusetts Institute of Technology.

The first KC Symposium brought 40 people from 11 organizations together to discuss general problems and issues surrounding KC implementation. The second KC Symposium expanded to 80 people from 28 organizations including AlliedSignal, Alcoa, British Aerospace, Chrysler Corporation, DARPA, Eastman Kodak Company, Ford Motor Company, Embry-Riddle Aeronautical University, General Electric, General Motors, 2 divisions of Honeywell, IBM, IDA, ITT, Lockheed Martin, MIT, NASA, NIST, Northrop Grumman, Pratt & Whitney, Quality Associates, Raytheon, Textron, 5 divisions of Boeing, United Space Alliance, University of Florida, University of Maryland, and Xerox. Thirteen presentations were given: AlliedSignal discussed implications of KCs on suppliers; GE discussed design for 6 Sigma; Xerox, Kodak, and Boeing gave overviews and examples of KC implementations; and IBM gave a presentation on the implication of statistical tolerancing.

Significant time was also spent discussing four issues: how to take a system view of Variation Risk Management; what do KCs mean to suppliers; should there be a US standard for KCs; and what are the cost implications and benefits of KC methodologies. In addition, several working groups were formed to continue discussions over the next year. These groups are Costs, Standards, Statistical Tolerancing, Process Capability Databases, Metrology, Supplier Relations, and Models and Tools.

Information about the conferences, working groups, and other KC resources can be found at http://cardamom.mit.edu/KC/kc.html.

5.4.2. KC Maturity Model

In conjunction with the Lean Aerospace Initiative, a series of site visits and interviews were made to assess the current level of maturity of KC practices in industry. The interview result was the KC Maturity Model. This model contains more than 20 practices critical to effective Variation Risk Management implementation.

Table 3: KC Maturity Model Practices

KC Identification Stage	The phase in which KCs are identified.
KC Definition	The existence of common definitions and methods within and between groups.
KC Prioritization	The process by which a set of KCs are ranked according to their importance.
KC Validation	The process by which the selection of the correct KCs is verified.
Documentation	The formal documents and processes by which KCs are transmitted between groups (e.g., design, manufacturing, and quality).
KC Flowdown	The process by which KCs are decomposed from a system or customer level to a piece part level.
Modeling	The computation and quantitative methods by which a product is evaluated. The models can be capable of measuring performance, variation effects, and potential failure modes.
Customer Interaction	The ongoing interaction between the customer and the product development organization.
Integrated Product Teams	The cross-functional teams used to develop the product.
Supplier Interaction	The interaction between the supplier and the product development organization.
Management Support	The leadership, resource allocation, and role that management needs to play to enable good KC use in the organization.
Incentive Structures	The organizational drivers that encourage the use of KCs and the resulting level of willingness of the product development team to participation in the methods and supporting practices.
KC Training	The formal courses, documentation, and ongoing training that an organization offers and supports.
KC Objectives	The stated goals and needs that define the scope of the KC effort.
Measurement Plans	The quality control plans implemented by the manufacturing organization to control and track variability throughout the product life cycle.
Process Capability Feedback	The process by which historical data on process capability is made available to functional organizations outside the manufacturing group.
Process Capability Uncertainty	Systematic identification and reduction of uncertainty in the process variability.
Design Changes / Robust Design	Design modifications due to an inability to achieve the function of the systems at a reasonable cost.
New Technology Introduction	New technology (product and process) is introduced, when it is robust, into a product development environment.
Cost Models	The ability to understand and quantify the cost implications of design decisions.
Reuse/Legacy Data	The ability to leverage and utilize existing product data and document as well as maintain new design documents in a form that is reusable.
Tolerancing & Dimensioning	The consistent application of good tolerancing practice.

For each of these elements, four levels of maturity are defined: none, reactive, semi-proactive, and fully-proactive. The maturity level of the *KC Identification* stage is given below and the rest of the maturity model can be found in the appendix.

Table 4: Maturity Model for *KC Identification*

Definitions	0: Not used at all.	1: Reactive	2: Semi-proactive	3:Fully Proactive

The phase in which KCs are identified.	None identified	KCs identified in production when quality problems occur. Triggers for identification of KCs include high rework, scrap, repair, or customer dissatisfaction.	KCs identified at the end of product design (after the design is completed but before the design is put into production). These KCs identify areas of potential cost and require extra control by manufacturing to ensure a quality product.	KCs are identified during the early design stages and are continually updated. They are identified where the design is not robust for the current manufacturing capabilities. Efforts are made to reduce the risk associated with KCs.

Level zero, *Not used at all,* corresponds to companies not executing any form of the practice. The *reactive* level is used to describe companies that only execute Variation Risk Management strategies when a problem occurs in production. The *semi-proactive* level corresponds to those companies using late in the design process when major design changes are not feasible. The *fully-proactive* level is reserved for companies that systematically identify, assess, and mitigation variation effects throughout the design process.

The model has been validated at a variety of companies and there is an ongoing effort to evaluate a variety of other companies.

The individual practices of the KC Maturity Model were placed on a square matrix and dependencies between practices were mapped. The interrelationships were originally based on observations from benchmark studies, training manuals, and KC symposium. The KC Group iterated through the relationships and discussed how each practice related to another. Then the matrix was lower diagonalized by an algorithm that optimizes the order of practices by minimizing interactions between practices. The resulting KC Practice Relationship Matrix is shown in Figure 5-8 .

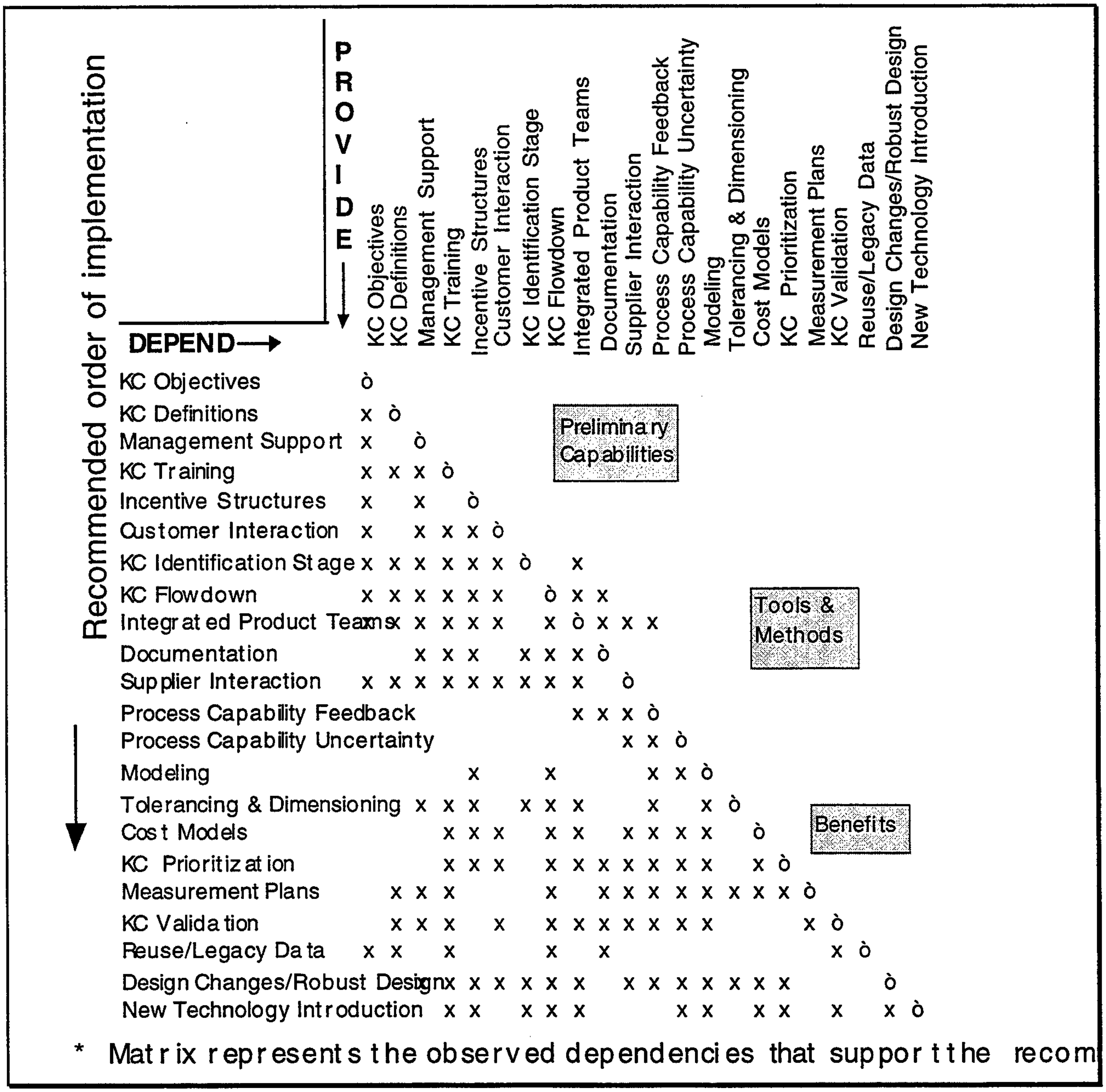

Figure 5-8: Key Characteristic Practice Relationship Matrix.

The KC Practice Relationship Matrix highlights three separate groups of coupled practices: Preliminary Capabilities, Tools and Methods, and Benefits. A significant finding is that each practice is sequentially ordered with respect to another and each group is sequentially ordered.

The first group is called Preliminary Capabilities. Practices in this group are KC Objectives, KC Definitions and Methods, Management Support, KC Training, Incentive Structures, and Customer Interaction. These six practices were defined as core elements for successful KC implementation.

The second group was named Tools and Methods – this group further enhances KC implementation success as long as Preliminary Capabilities are already in place. The following are eight practices are within this group: KC Identification Stage, KC Flowdown, Integrated Product Teams, Documentation, Supplier Interaction, Process Capability Feedback, Process Capability Uncertainty, and Modeling. These eight practices all tend to be coupled and should be performed concurrently for optimal success.

The final group, Benefits, has eight practices. These practices can be more easily utilized after the other two groups of practices are institutionalized. The following are practices in the Benefits group: Tolerancing and Dimensioning, Cost Models, KC Prioritization, Measurement Plans, KC Validation, Reuse/Legacy Data, Design Changes/Robust Design, and New Technology.

During the second KC symposium, companies were asked to fill out the KC Maturity Model.

The participants were asked to specify what percentage of their company was operating at what level of maturity. For example, one company filled out that 10% of their company had no customer interaction, 30% reactively worked with their customer, 40% semi-proactively, and 20% proactively. These measures were then averaged across all respondents. In analyzing the data, we found that respondents were clustered into two groups. There was a correlation between lower maturity and those that produced products in low volume and whose products had a long life span (i.e., aircraft design). On the other hand, companies that had faster design cycles and who produced products in higher volumes tended to be more mature.

This section will use practices in the Maturity Model to highlight differences and similarities in high volume and low volume industries.

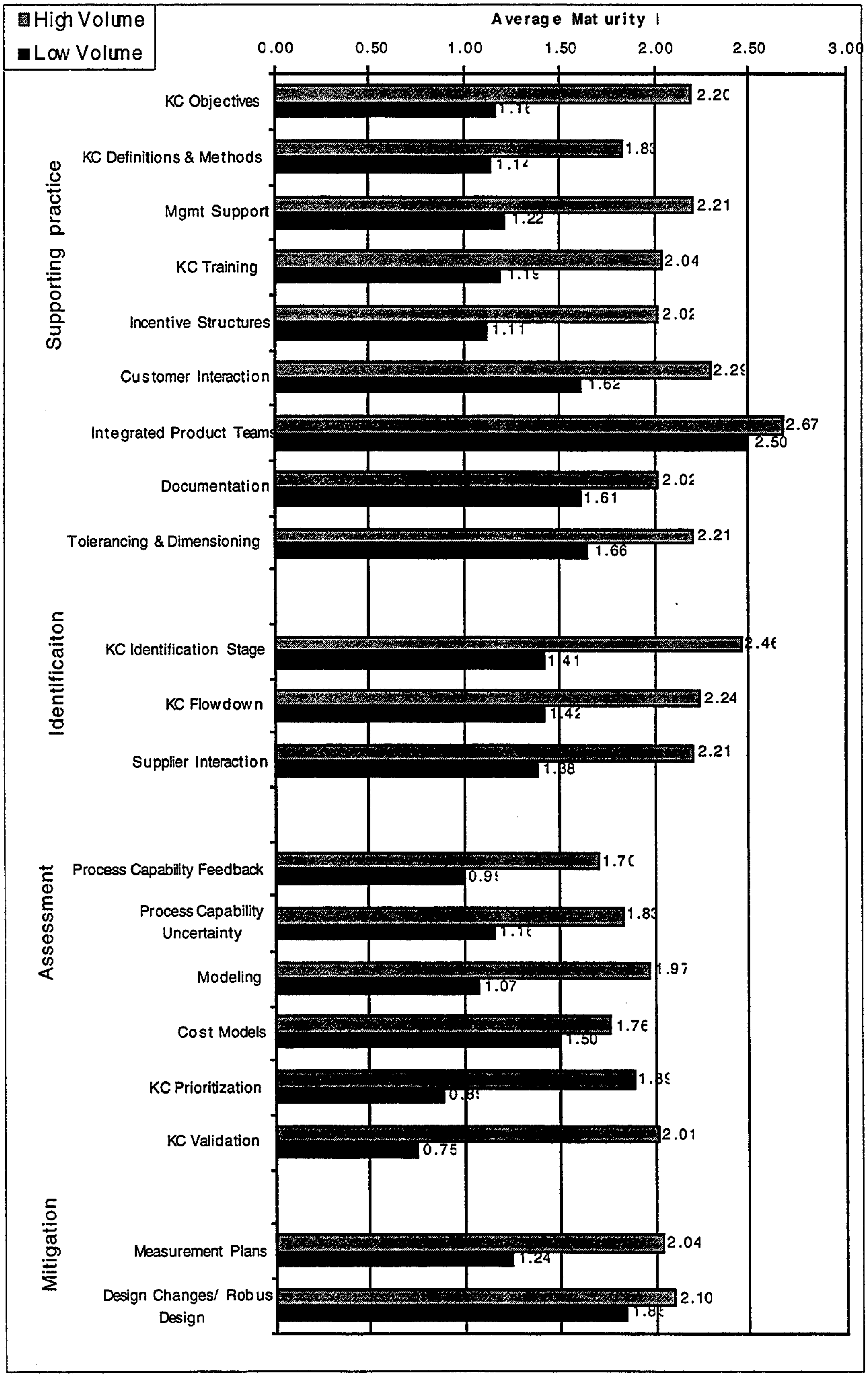
High Volume
Low Volume
Average Mat urity I
0.00
0.50
1.00
1.50
2.00
2.50
3.00
Supporting practice
KC Objectives
2.20
KC Definitions & Methods
Mgmt Support
2.21
1.22
KC Training
2.04
Incentive Structures
1.11
Customer Interaction
Integrated Product Teams
2.67
2.50
Documentation
1.61
Tolerancing & Dimensioning
2.21
1.66
Identificaiton
KC Identification Stage
KC Flowdown
2.24
Supplier Interaction
2.21
Assessment
Process Capability Feedback
Process Capability Uncertainty
Modeling
1.07
Cost Models
1.50
KC Prioritization
KC Validation
2.01
0.75
Mitigation
Measurement Plans
2.04
1.24
Design Changes/ Robus Design
2.10

Figure 5-9: Results from Maturity Assessment

Figure 5-9 shows the results for the KC maturity survey. Assessments are divided into four groups: support, identification, assessment, and mitigation. Many conclusions can be drawn from the data.

The trends for low and high volume companies are similar. For high volume companies, Support KC Practices are well established. KC practices are executed during both design and ramp-up. Management Support emphasizes tangible known practices. These are Customer Interaction, Integrated Product Teams, Dimensioning & Tolerancing, KC Identification Stage, KC Flowdowns, Supplier Interaction, Cost Models, and Robust Design. Many of these practices have textbooks, manuals, and articles that describe procedures, methods, and case studies. This increased awareness of these practices will result in a higher maturity level. Management is able to understand and support these KC practices and the organization is better able to apply these KC practices. For low volume companies, the trend in Support Practices correlating to performance in other management supported activities is similar. The difference is that all low volume practices have a lower maturity. This is because of the initial KC Objectives targeting reduction of variation in production.

Identification Practices are performed well for "high risk / high probability of occurrence" areas and for "low risk / low probability of occurrence" areas. If risk and probability of occurrence are high, then mitigation occurs; if they are low, nothing is done. In some cases, "high risk / low probability of occurrence" and "low risk / high probability of occurrence" areas are not completely assessed because of schedule pressure and a lack of understanding how systematic variation propagates. For Assessment KC Practices, a lower degree of understanding of these practices contributed to lower maturity level for these six practices.

Another trend is that KC practices, which depend on information from many other practices, tend to have a lower maturity level. This trend is not always consistent with the collected data. This inconsistency in this trend is seen in practices such as Cost Models, Measurement Plans, and Robust Design. The inconsistency can be linked to the existence of information about these topics. In general, it is easier to increase the maturity level of a practice that is dependent on very few other practices.

5.4.3. KC Tool

To address the needs identified in Section Summary and KC Maturity Model, a computer tool, *KC Tool*, was developed by the author and her students. The tool has three goals: identifying 1) what customer requirements are at high risk, 2) what is the effect of inexact information on results

provided by the analysis, and 3) to quantify costs and benefits of variation reduction strategies. This tool takes, as its input, the key characteristic flowdown, relationships between system and feature KCs, expected variation, inexactness of input information, and costs associated with variation reduction.

This report will review the data model used by KC Tool and one example of a quantitative analysis: variation reduction optimization. Several papers impacts have been written by the author and her students that explain methods to quantify variation quantify variation (Lee and Thornton 1996a), uncertainty calculation (Thornton 1996b), basic mathematics of risk management using KCs (Thornton 1997), and details of variation reduction methodology (Thornton 1998).

5.4.3.1. Data Model

The data model is based on a hierarchical description of variation, also termed a *Key Characteristic (KC) flowdown.* KC Tool was developed to provide an experimental environment in which analysis tools could be built and tested.

The KC flowdown model can be enhanced to enable quantitative evaluation of variation. (Lee and Thornton 1996b; Thornton 1996a; Thornton 1996b; Thornton 1997) by including a model of the relationships between feature level and system level variation. These types of relationships are typically available in product development organizations and are modeled here as a linear relationship. An example is shown in Figure 5-10. The figure demonstrates how an estimate of drag can be calculated from step and gap sizes.[9] Aerospace drag/gap relationships are typically derived from computational fluid dynamics (CFD) analyses or wind tunnel models. Step size can be modeled based on the geometry of the part.

[9] Steps and gaps refer to the interfaces between the aircraft skins on the top surface of the wing. Any excess gap (i.e., the distance between the panels in the plane of the wing surface) or steps (i.e., the distance between the panels perpendicular to wing surface) will result in excess drag. Each of the steps and gaps are created by other features in the wing.

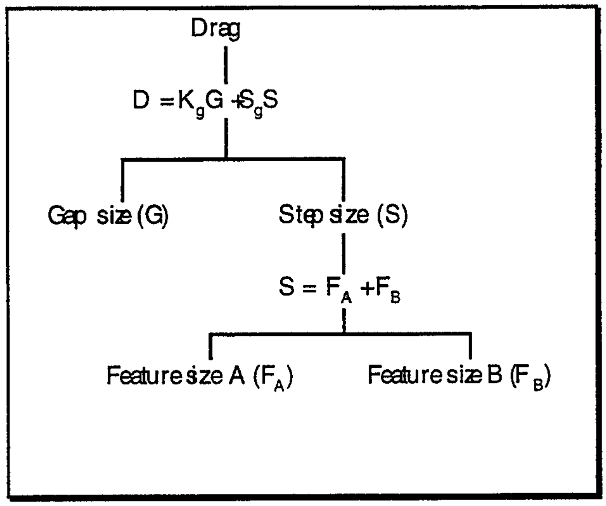

Figure 5-10: Enhanced KC Flowdown

Once the model is built, the variation in the "leafs" of the tree can be propagated up through the tree using root sum squared (RSS) methods or Monte-Carlo simulation. Final variation in system requirements is compared against allowable variation to determine what areas are not robust to existing variation. This type of model is simple, but can be used early in the design process when geometry is not available.

The KC Tool models two product descriptions –product assembly architecture and KC flowdown – in the main window (a sample is shown in Figure 5-11). The boxes describe a hierarchical decomposition of the assembly or manufacturing processes. They also are used to help organize the KC flowdown. Figure 5-11 shows a screen dump for a hypothetical decomposition for an aircraft. First, the trailing edge, main torque box, and leading edge are assembled to create the wing. In final assembly, the fuselage, wing, and tail are brought together to assemble the final aircraft.

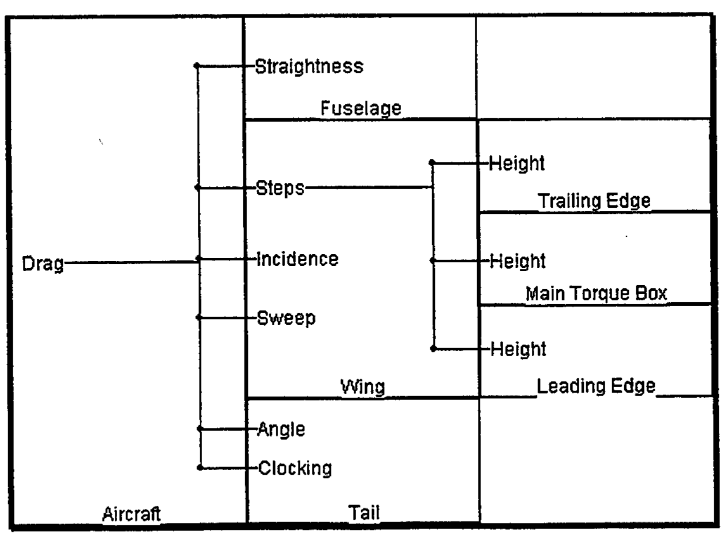

Figure 5-11: KC Flowdown from KC Tool

The second part of the model, the KC flowdown, is superimposed on the product decomposition. For example, steps, incidence, and sweep of the wing contribute to the final system level KC – drag. Each KC has a variety of information associated with it. Figure 5-12 shows an example of the data associated with the height of the main torque box. For example, the upper specification limit (USL) (referenced from nominal), lower specification limit (LSL) (referenced from nominal), and nominal values are shown. In addition, information about the process improvement, part, rework, and assembly costs are captured. This information will eventually be linked to process capability data systems available in most companies.

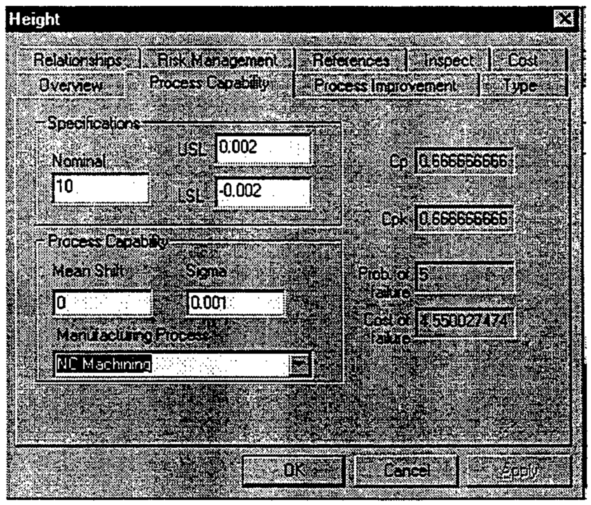

Figure 5-12: Example of KC Data

5.4.3.2. Variation Reduction Optimization

This report focuses on one aspect of the KCTool: a model for variation reduction. Variation Reduction (VR) is a term applied to a broad set of tasks performed by process improvement teams[10]. VR works to reduce variation where it causes significant excess cost and a design or process change is not economically feasible. These teams are usually responsible for continual process improvement once a product is in production. This is especially important in products that have a long production life and/or are produced in high volumes. Any product cost that can be pulled out once it is in production translates into pure profit or into an ability to drop the price of a product.

[10] This section is based on observations by the author of a wide variety of companies and their practices. Due to proprietary issues, specific names and practices are not given.

VR teams generally have a fixed number of people and a fixed budget. Therefore, VR teams are limited in the number and scope of the projects that they can take on. In general, they are a fire-fighting team that acts to reduce variation in areas of largest pain. VR target areas are generally raised by other function groups such as production. For example, manufacturing will highlight current "hot" areas where unacceptable levels of rework, scrap, repair, or labor exist.

Most of the VR teams we have observed have been very effective at removing variation from targeted areas. However, they tend to be a fire-fighting group rather than a problem prevention group. They tend not to be involved in the early design stages. Furthermore, it has also been observed that they tend to apply their tools where the biggest problem appears without strategically allocating their resources. For example, two features, A and B, contribute linearly to feature C. All features have normal distributions. Feature A has a standard deviation from mean of 0.003 inches and feature B has a standard deviation from mean of 0.002 inches and they both contribute to feature C such that the standard deviation from nominal of C is 0.0036 inches ($\sqrt{.002^2+.003^2}$). If the target variation from nominal for C is set at 0.0028, VR teams will almost always target the feature A (the "larger" contributor) and reduce it to.002. However, it may be more cost effective to reduce feature B to.001. When B is chosen, the decision is often based on qualitative assessments of cost not quantitative calculations of the optimal resource allocation.

In order to better determine how to allocate limited resources in a VR team, several tools are needed. First, a method is needed to determine the cost/benefit for a given VR plan. Second, a team should be able to optimize a VR plan for a given resource level. Third, the tool should determine what resource expenditure would provide the best returns.

A methodology has been developed that quantifies the costs and benefits of variation reduction plans used to improve existing processes. It describes a model and prototype software system that quantify the cost impact and benefit of a VR plan, determine the optimal VR plan for a set of constrained resources, and optimize the resource investment level to maximize return.

The variation reduction optimization sets both the groups of features to improve, as well as the level of reduction for each of the features. Traditional gradient decent algorithms are not appropriate for this optimization problem because the search space contains a mix of discrete and continuous variables. In addition, many local minimums exist in the search space. Both factors can make it difficult for traditional optimization algorithms to find a global minimum. Stochastic algorithms (e.g., Genetic Algorithms or Simulated Annealing) are more appropriate because of their ability to robustly find the

global minimum in mixed discrete and/or continuous spaces with multiple local minimum.

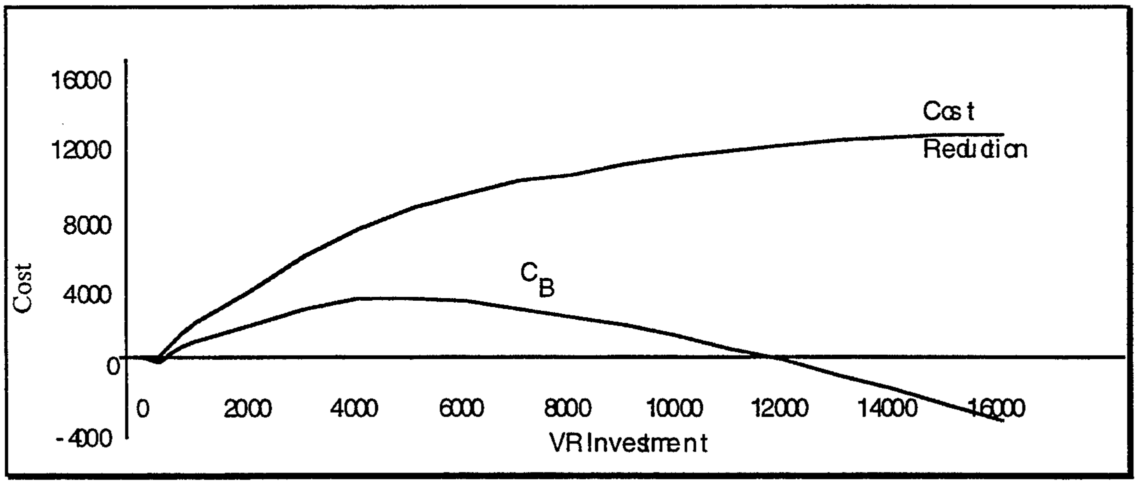

Figure 5-13: Variation Reduction Optimization

5.5. Results and Recommendations

The area of Variation Risk Management and Key Characteristics is a critical area that requires a great deal of improvement and further research. We have been able to identify what is required to effectively manage variation risk; however, significant gaps exist between the current state of the art and the best practice state. The most important is the lack of tools and methods to integrate models, process capability and costs (as well as a lack of databases to support these tools). The tools should enable effective assessment of risk and identification of the most appropriate risk mitigation strategy.

Work is continuing on this problem through the Center for Innovation and Product Development as well as the Lean Aerospace Initiative. In addition, Prof. Thornton was awarded a NSF Career Award grant to continue fundamental research in this area.

5.6. Papers Published on Key Characteristics

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Thornton, A. C. (1996b). Key Characteristics: Risk management using modeling and simulation. Working paper. Cambridge, MA, MIT.

Thornton, A. C. (1997). "Using Key Characteristics to balance cost and quality during product development". ASME Design Technical Conferences, Sacramento CA, ASME.

Practice	Level Definitions	0 Not used at all	1 Reactive	2 Semi-Proactive	3 Fully Proactive
KC Identification Stage	The phase in which KCs are identified.	None identified.	KCs identified in production when quality problems occur. Triggers for identification of KCs include high rework, scrap, repair, or customer dissatisfaction.	KCs identified at the end of product design (after the design is completed but before the design is put into production). These KCs identify areas of potential cost and require extra control by manufacturing to ensure a quality product.	KCs identified during the early stages of design and are continually updated. They are identified where the design is not robust for the current manufacturing capabilities. Efforts are made to reduce the risk associated with KCs.
KC Definition	The existence of common definitions and methods within and between groups.	Not clearly stated.	KCs are defined by the teams identifying and using them. No consensus or communication between functional groups about the criteria for identification or the implication once identified.	A common definition is documented but variability exists between groups.	A common manageable set of understandable definitions and classifications exist. Common understanding of what a KC is and what it means.
KC Prioritization	The process by which a set of KCs are ranked according to their importance.	None.	KCs are ranked according to high cost of rework, scrap, or repair costs.	Qualitative ranking system based on assumptions of potential problems.	Ranking based on quantitative measures including historical process data and models.
KC Validation	The process by which the selection of the correct KCs is verified.	None.	The set is considered valid if a reduction in rework, assembly hours, productions cost is seen.	Modeling is used at the end of the design process to identify areas where there is a potential risk. The identification of the correct set is validated by problems seen once in production.	Early use of prototypes and virtual models to ensure that the correct set is identified. Uncertain processes are validated prior to full production.

	Level Definitions	0 Not used at all	1 Reactive	2 Semi-Proactive	3 Fully Proactive
Integrated Product Teams	The cross-functional teams used to develop the product.	None.	Formed when there is a problem in production.	Formed during the product development process. They react to potential problems in fire-fighting mode.	IPTs are formed at the start of the design process. They have a clear set of objectives and proactively attempt to find and eliminate problems before they arise.
Supplier Interaction	The interaction between the supplier and the product development organization.	Drawings and designs handed over the wall.	Suppliers brought in only if a problem occurs.	Suppliers are brought in at the end of the design to verify the producibility.	Suppliers are integrated with the IPTs to evaluate producibility. They make suggestions where the design may not be robust and where relief in requirements will have a significant impact on cost.
Management Support	The leadership, resource allocation, and role that management needs to play to enable good KC use in the organization.	Not Applicable.	Mgmt. encourages the use of KCs but resources are not properly allocated.	Mgmt. supports engineering teams to use KCs, but KCs are ignored if larger problems arise.	Mgmt. understands the need for KCs and they advocate and help facilitate their use within the company.
Incentive Structures	The organizational drivers that encourage the use of KCs and the resulting level of willingness of the product development team to participation in the methods and supporting practices.	None.	Forced by contractual or management requirements and performed as a box checking exercise.	Performed as a separate, independent process that requires people to "put KCs on drawings" but not at the expense of drawing release. Some benefits of KC utilization are acknowledged.	Incentives to effectively put KCs on drawings. KC practices are fully accepted and performed as a seamless, integrated process. The processes are seen and demonstrated as an enabler to achieve both low cost and robust designs.

	Level Definitions	0 Not used at all	1 Reactive	2 Semi-Proactive	3 Fully Proactive
KC Training	The formal courses, documentation, and ongoing training that an organization offers and supports.	No training program.	Documents about KCs given to engineers and suppliers. They are told to "do KCs" without training.	Training is done but the examples are not applicable to realistic design areas. No follow-up or long term assistance is performed to ensure understanding or proper use.	Programs are developed to increase skills in design and manufacturing. Training occurs "just in time." Training addresses, through real examples, the problems that teams are facing. Follow-up training and coaching available to ensure proper application.
KC Objectives	The stated goals and needs that define the scope of the KC effort.	No stated goals	Goals are to reduce cost in current production.	Goals are to identify high cost and high-risk areas before the product is transitioned into production.	Goals are to reduce cost, risk, and time-to-market through front-end attention to areas of low robustness, high cost, and high risk. These objectives are clear throughout the extended enterprise.
Measurement Plans	The quality control plans implemented by the manufacturing organization to control and track variability throughout the product life cycle.	No measurement plans.	Measurement plans implemented to solve problems identified during production.	IPTs set measurement plans based on KCs resulting in too large of a set of measurement points. These measurement points are not changed as processes are validated.	KC driven measurement plans used to validate where 1) capability prediction is uncertain and 2) design is not robust. Plans change through the product life as processes and products are validated.

Practice	Level Definitions	0 Not used at all	1 Reactive	2 Semi-Proactive	3 Fully Proactive
Process Capability Feedback	The process by which historical data on process capability is made available to functional organizations outside the manufacturing group.	No feedback into design.	Capability fed back when problems occur.	SPC data captured and recorded for a variety of features, but data is hard to find and is not used throughout the organization.	SPC data fed back to design, updated, and is available electronically in a form that is painless to use.
Process Capability Uncertainty	Systematic identification and reduction of uncertainty in the process variability.	No measure of uncertainty.	If a problem occurs in production, measurements are imposed to reduce uncertainty.	Uncertainty in process capability is acknowledged and discussed. A manufacturing plan is put in place before production begins to reduce uncertainty.	Team has a system view of capability uncertainty and deploys effective control plans to maintain quality and work toward process improvement.
Design Changes / Robust Design	Design modifications due to an inability to achieve the function of the systems at a reasonable cost.	None.	Late design changes are made to reduce significantly high production cost.	Reactive changes are made to areas found not producible during production ramp-up.	Changes are made by design and manufacturing during the design stage by means of an iterative design process to increase producibility.
New Technology Introduction	New technology (product and process) is introduced, when it is robust, into a product development environment.	No new technology is introduced or no reaction occurs to problems caused by new technology.	Problems with new technology addressed during ramp up and production.	Failure modes are identified before product launch and monitored or tested out.	Technology robustness issues are identified prior to product development; design decisions and control plans are utilized to ensure robustness of the final product.

Practice	Level Definitions	0 Not used at all	1 Reactive	2 Semi-Proactive	3 Fully Proactive
Cost Models	The ability to understand and quantify the cost implications of design decisions.	Not measurable.	Able to identify the high cost or rework, repair, and scrap (RR&S) once in production. Unable to quantify these costs accurately.	Identify potential high cost of RR&S in the development stage.	Costs are used to identify where changes in design should occur. Able to tradeoff the costs of redesign vs. inspection and rework.
Reuse/Legacy Data	The ability to leverage and utilize existing product data and document as well as maintain new design documents in a form that is reusable.	KCs are re-identified and legacy data is not considered.	KCs are reused only when conditions are considered identical.	Reuse is limited. Legacy data is randomly updated and generally unstructured.	The product/process relationships are understood and the KC data is maintained, updated, and reused where applicable.
Tolerancing & Dimensioning	The consistent application of good tolerancing practice.	Not considered. GD&T not used.	Tolerance based on old designs. GD&T applied randomly.	Reviews used to ensure correct and consistent use and application of GD&T.	Automated systems throughout the organization to ensure consistent application of GD&T.

6. Mathematical and Computer Models of Mechanical Assemblies

This section reviews the state of the art in modeling assemblies in CAD systems. This is an important matter because such models provide the infrastructure for a design process that permits assemblies to be designed systematically. A brief outline of such a systematic method is given in this section and elaborated in Section 6. These assembly models capture KCs quantitatively. They also provide the underlying basis for qualitatively tracing contact chains along supply chains and permitting integration risk to be identified.

6.1. Motivation

It is commonly accepted that some kind of concurrent design or integrated product teams represent the best practice for designing products that can be manufactured effectively. At most companies, this process is carried out by means of meetings between domain experts who provide feedback based on their experience. It was recognized about 10 years ago that early consideration of assembly would help this process by providing an integrative focus. [Nevins and Whitney] However, even today, systematic tools to support this or any other approach are few. Our research has convinced us that assembly remains a promising vehicle for promoting an integrated approach that encompasses performance, quality, and the realities of outsourcing. A computer-based model of assemblies would be very helpful in providing the base for systematic design and evaluation tools to support this approach. The benefits, discussed below, are:

- facilitation of a top-down design approach based on the method of KCs

- creation of a structure for storing and flowing down KCs

- creation of an organized repository for knowledge and information about assembly in general and specific parts and assemblies in a given product that can be used to improve subsequent designs or to help diagnose assembly problems

6.2. State of Implementations of Assembly in Commercial CAD

Until very recently, CAD systems could not represent assemblies as assemblies. The computer power necessary to assemble and display models of many parts at once was lacking. With the advent of solid modeling, a kind of assembly model has come into being. This is often called "electronic

preassembly." It permits parts to be located in space in the nominally correct locations in world coordinates (such as buttline, waterline, and station line in aircraft terminology with the origin at or slightly ahead of the front of the aircraft). An interference analysis can then be invoked, mis-sized, mis-located, or mis-shapen parts can be detected, and the errors can be fixed. Since such errors were hard to detect in complex assemblies designed on paper, a great many problems were averted by means of this method.

Current models still fall short in important ways. First, they do not represent the effects of variation. As one engineer put it to us, "Electronic parts always fit because they always hit the nominal dimensions." A false sense of security can result. Second, and more important, such models cannot be constructed from a pre-designed plan for constraint, that is, a strategy indicating which degrees of freedom of a part are controlled by which other part or fixture.[11] Typically, such decisions are the province of tooling designers anyway, but they often come into the process late and must work with the parts as designed. Provision for such decisions earlier, where they belong, would require reorganizing parts of the design process. Third, a consequence of the second, current CAD models do not contain any information about how the parts assemble to each other or even which parts are actually mated as contrasted with merely touching or being near each other. For this reason, there is no built in information to support an assembly tolerance analysis because the information needed to build up a tolerance chain is absent. Tolerance analyses conducted today with commercial software such as VSA must be done by a domain expert who constructs the tolerance chains manually from information provided by designers.

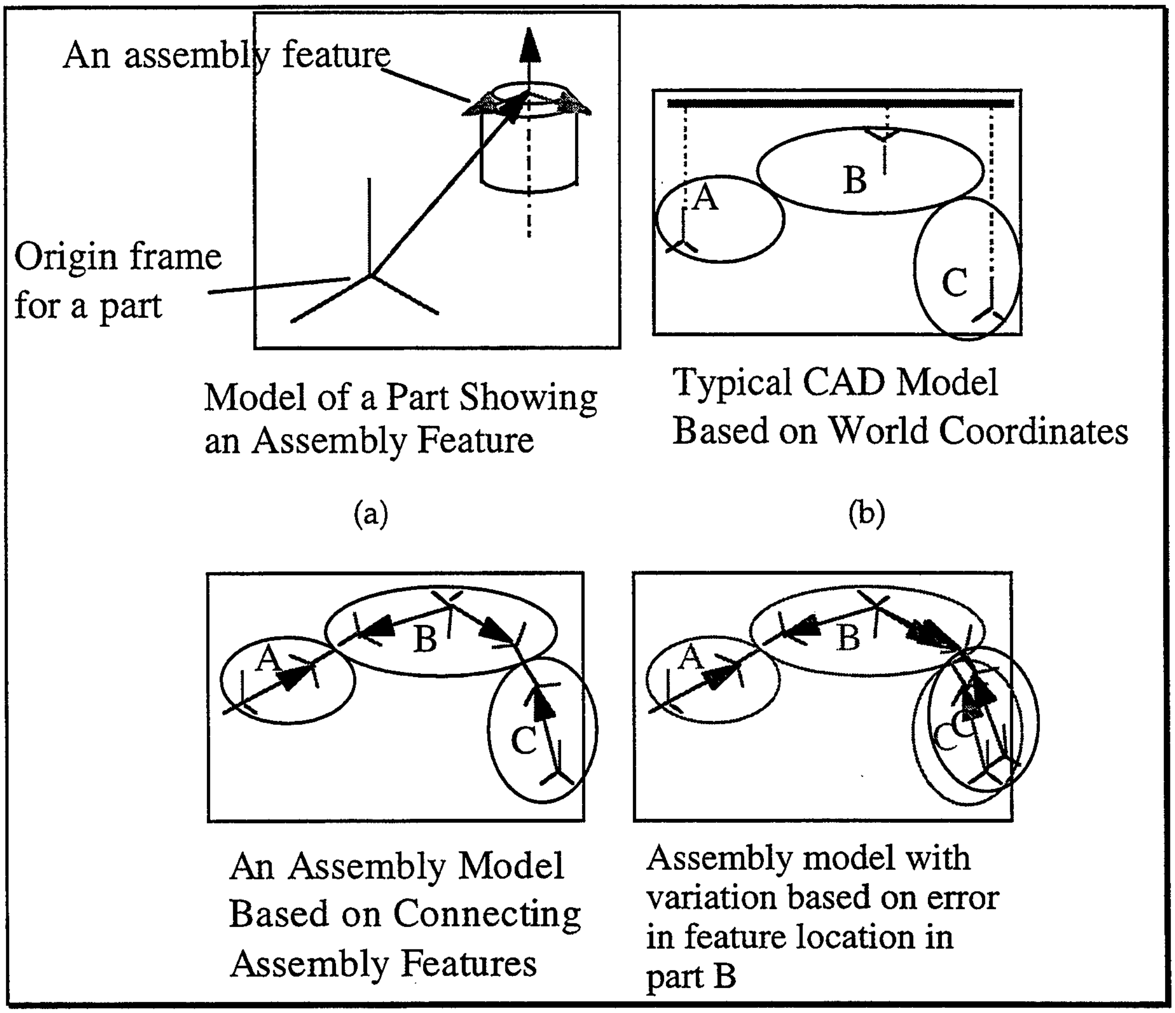
The methods described in Section 8 of this report are intended to support creation of a constraint structure for assemblies that provides information on nominal part location as well as the logic of dimensional control and tolerance chains.

6.3. Feature-based Design of Assemblies

Computer-based models of assemblies are at least as old as fundamental robotics research from the 1970s [Simunovic, Popplestone and Ambler]. Each part is given its own origin coordinate frame, and each place (now called an "assembly feature") where it connected to another part is given a coordinate frame as well. The relative locations of these frames are easily calculated. If one specifies that "this place on this part connects to that place on that part," then it is easy to construct a mathematical model of the assembly that locates every part nominally in space relative to its neighbors. This is a true assembly model. An early implementation of this was called "feature-based

[11] In fact, there is considerable evidence that designers are not sensitive to the issue of constraint and often design over-constrained assemblies. [Kriegel]

design for assembly." [De Fazio et al] Figure 6-1 sketches the concept of feature-based design for assembly and compares current world coordinate CAD models of assemblies with a true assembly model.



(c) (d)

Figure 6-1. World and Relative Assembly Models. (a) An assembly feature, such as a peg, is located relative to the part's origin coordinate system by a coordinate transform represented by the arrow. (b) In a world coordinate model, parts are located in world coordinates so that they are touching each other at the mating features, but the fact that they mate there is not part of the model. (c) In a feature-based assembly model, the features are mated mathematically by joining their coordinate frames. By conducting a series of coordinate transforms, (following the arrows from frame to frame) one can navigate from part to part through the assembly. (d) If there is variation in sizing, positioning, or orienting the features within the parts, the cumulative effects of these variations can be calculated by suitably adjusting the positions and orientations of the frames and tracing the revised locations along the arrows.

6.4. Sketch of a top-down design process for assemblies

Before there was CAD, people who designed on paper used a top-down process for designing mechanical assemblies. The first step was a skeleton layout that showed the basic datums, mating faces, centerlines, and so on. Onto this skeleton the layout person placed outlines of parts. From this layout a rough assembly drawing was made, showing the approximate shape of each part as it lay on a centerline, abutted a datum or mating surface, or abutted another part. Then a detailer drew each part in detail and provided dimensions and tolerances. Finally, a checker rebuilt the assembly drawing using the detail drawings and their dimensions, and checked to see if everything fit. The career ladder for a designer ran from detailer to assembler to layout to checker.

The advent of wireframe CAD spelled the end of this process, focusing programming facilities on the detail phase. People with checking and layout skills are now few. Only recently have CAD systems been able to do some checking by means of interference analysis. When layout people and their skill were lost, design of assemblies became a bottom-up process in which parts were detailed and then fitted together. Tolerances are attached only to parts, and tolerance analysis is largely manual or is done with additional software that often requires domain experts and some translation of data.

It is necessary to restore the ability to create top-down design of assemblies so that KC delievery can be guaranteed and assembly information can be captured and used for tolerancing and corrective action in the factory. Such a process begins with the specification of function and one or more physical concepts. Key performance parameters are obtained from customer requirements lists and converted into KCs (particular dimensions and tolerances on the assembly). A dimensional skeleton should then be proposed with the twin goals of establishing the positional constraints between prospective parts and of controlling the key dimenions.

Parts should be added to this skeleton using the roughest geometry that is sufficient to show how their positions and orientations would be controlled. Control would be established by focusing detail on the locations or features on the parts that act as interfaces to the parts they assemble to. These interfaces are called assembly features. Each kind of feature mate (peg to hole, peg to slotted hole, etc) controls from one to six degrees of freedom of the mating part. A model of the type shown in Figure 6-1 (c) would be built up as each part and its mating features was added. Features could be drawn from a menu for this purpose and attached to the skeleton to show how and where parts eventually will join each other. Once the assembly features have been chosen, checking could be done to see that each part is properly constrained and not over- or under- constrained, unless underconstraint is desired for functional reasons. A tolerance analysis on the skeleton could

also be performed at this stage to check that the KCs are under control. Detailed part geometry could be added to the rough parts at any time, once the overall coherence of the dimensional control plan, the mating features, the constraints, and the tolerances had been checked.

This process follows the suggestions of Taguchi, who proposes that design take place in three phases:

• system design (here, creation of the dimensional control skeleton)

• parameter design (selection of mating features and checking of constraints)

• tolerance design (error analysis of the skeleton and features)

Taguchi says that too often the first or even the first two steps are skipped or given too little attention, and people try to achieve everything from step three. This usually means tightening tolerances, which is a costly approach. A poorly designed skeleton or unconstrained/overconstrained parts will create a poor assembly which cannot be rescued by tightening the tolerances. In fact, loosening clearances may be needed to reduce over-constraint.

Another way to characterize this approach is by using the methods and vocabulary of system engineering. The process described above consists of defining and managing the interfaces between the parts first, and then detailing the rest of the parts.

In Section 8, this method will be laid out in detail. The skeleton will be named the Datum Flow Chain, which is a graph that shows how parts and fixtures locate each other and deliver KCs. Section 12 will describe prototype software that enables designers to create these chains, add features, check constraints, generate assembly sequences, and check tolerances.

6.5. References

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7. Design of KC Delivery and Identification of Integration Risk During Concept Design[12]

7.1. Introduction

Concept design is the phase where a product's functional requirements are identified and converted into a plausible set of physical elements in a plausible physical arrangement. *Product architecture* is the name now given to the scheme by which functions are assigned to physical elements and the interactions between those elements are defined.[1, 2] Every product has an architecture as a result of concept design.

Architectures are said to differ in the degree to which they are *integral* or *modular*. In a modular product, each function, and the associated KCs, is mapped to one or a few physical elements. Modular products are attractive for a number of producibility and outsourcing reasons because the individual modules can be designed and made somewhat independently. In an integral product, one or more functions and the associated KCs may share physical elements, or many physical elements may work together to deliver a function. We call such functions *integral characteristics*. Integral products are also attractive for a number of performance reasons, such as weight or energy consumption. As product concepts are optimized for performance, integral characteristics enter their architecture. As they are optimized for producibility and outsourcing, modular characteristics enter.

Along with integral characteristics comes what we call *integration risk*: the risk that apparently properly made elements will not function as desired when assembled, or will require long error correction or adjustment. Integration risk rapidly spawns cost and schedule risk because integration problems are usually found late in product development and are hard to diagnose.

A design team needs a way to both establish the architecture during concept design and to assess each concept's degree of integration risk along with the other advantages and disadvantages of integrality or modularity. We propose the *chains* method to aid the team in this process. A chain specifically identifies the physical elements that are involved in delivering an integral characteristic, using information that is customarily available during concept design. It is important to understand that products having multiple physical parts may appear to be modular, yet can still harbor integral characteristics and integration risk.

The chains method is designed to address several important features of concept design that are often overlooked in practice and theory. First, a

[12] This Section is adapted from [Cunningham and Whitney] and is based on [Cunningham 1998].

concept design team is usually highly cross functional, and the members from different functions want very different things from the product. While performance engineers can think in functional terms, producibility and outsourcing people must think in physical terms. Thus a concept has to be fleshed out into visible physical patterns in order for two of the three main participants to be effective. Second, these different groups speak largely different languages, and expressing their concerns so others can understand them can be quite difficult. Performance engineers have the upper hand because they have access to computerized performance analysis tools, whereas the other participants must rely on experience and often thereby lose the argument even if they should win. Third, there is often too little detail during concept design to permit conventional DFX tools to be applied to help the producibility people explain their concerns. The answer is not to provide more detail because that would bog the process down, and in any case such details could well be incorrect. Finally, our research has shown that integration risk is not addressed during most concept design activities because it seems to be invisible, along with other aspects of the integral-modular tradeoff. There are no design tools to highlight it like there are for stress or vibration. In fact existing tools like 3D CAD tend to focus people on single parts to the exclusion of factors that connect them together. Integration becomes a fact and a threat only when assembly is attempted and problems are found.

The chains method attacks these problems in the following way. First it is pictorial and can be understood by all team participants who can visualize the product and its main candidate modules, even in sketch form. Second, it reveals the number and physical locations of all the elements that participate in delivering each main function. Third, it clearly shows when functions share elements or when there is likely to be conflict between delivery of different functions. Fourth, it permits measurement and ranking of integration risk using calculations that anyone can carry out without using judgment. These measurements follow in the tradition of other DFX methods in requiring only enough detail to permit basic classification and scoring.

To repeat: every product has an architecture and every architecture has some degree of integration risk. Either the design process will include deliberate steps that actively generate each concept's architecture and evaluate its risk, or else the team will let the architecture emerge as a by product of other decisions, and integration risk will attack the process later when it can do great damage to cost and schedule.

The goal is not to produce a concept with zero integration risk. This is not only unattainable but probably undesirable because it suppresses integrality altogether, along with its advantages. Rather the goal is to know by

the end of concept design what the integration risk is and where it is likely to lie, so that later steps in the design process can mitigate it.

This Section presents the procedure for capturing chains and metrics used to evaluate them. Section 7.2 describes related work, with a focus on the physical and mathematical basis of chains. Section 7.3 outlines the overall method in which the chain capture procedure fits. Section 7.4 describes the procedure in the context of a set of principles that apply the physical basis so that it is applicable during concept design. Section 7.5 describes an aircraft structure example that illustrates the procedure and emphasizes how important it is that such analysis occur during concept design. Section 7.6 introduces the types of metrics that can be applied during concept design, and Section 7.7 illustrates the metrics by analyzing the aircraft structure example. Section 7.8 presents conclusions. The complete method and the metrics are discussed in [3, 4].

7.2. Definition of a Chain and Its Basis in Prior Research

Product architecture is currently receiving a great deal of attention in literature related to product development. The simple categorization "modular" and "integral" appears to have been posed first by Ulrich [1], followed by maturation of the ideas in Ulrich and Eppinger [2], in an attempt to unify common elements of the design theory, systems engineering, and management literature. Their work also presents an openness to modular and integral approaches, while the design theory and systems engineering concepts on which their work is built [5, 6, 7, 8, 9] state that modular is the ideal.[13] Empirical evidence shows that modular designs do not always lead to successful products [11], and many simple and complex products exhibit some degree of integrality in the characteristics that distinguish them from their competition [12]. Our work further contributes to a general language for product architecture types, with due attention to integral character [3, 4].

A number of assembly models based on graph techniques are applicable to our goal for using chains as a map of a function to its physical elements. The most recent is the Datum Flow Chain (DFC) [13] (see Section 8), an attributed directed graph that shows how the relative locations of parts in an assembly are determined. The physical basis of all such techniques is the same: the position of a feature on any part of an assembly relative to some base reference frame, or relative to a feature on another part, lies at the end of a chain that describes how the parts are connected to each other, as outlined in Section 6. Early roots are traceable to work in the fields of robotics by Simunovic [14] and assembly modeling by Lee and Gossard [15].

Figure 1 shows the physical basis in the context of an assembly where we are interested in the relative position of parts a and b. The mathematical basis

[13] The interaction of this work with design theory is discussed in [10].

of chains takes the form of a 4x4 matrix (each T_i) whose content is the position and orientation information [16] for each of the reference frame relationships shown in the chain (each arrow in Figure 1 is called a "link"). The same assembly models that define the nominal delivery of such a dimensional attribute can be used to model the variation associated with it. Variation analysis in assemblies is an active field, with many current efforts summarized in Chase and Parkinson [17]. Whitney et al [18] develop the contents of 4x4 matrices that represent variation, and describe a closed form method for calculating the varied position in an assembly.

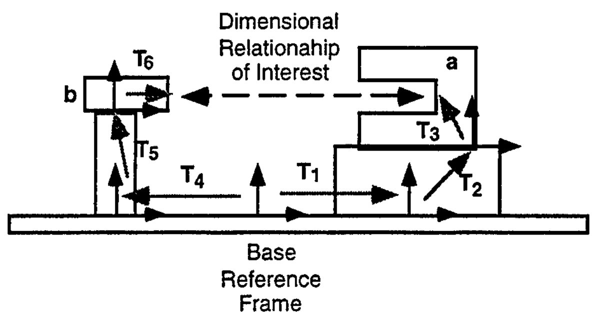

Figure 7-1. Nominal build up of relative part positions in an assembly. This figure uses the models presented in Figure 6-1(c) to link parts to each other in an assembly. T_i represents each 4x4 matrix transform that relates the position of the successive part in the assembly, starting from the base. The dimensional relationship of interest is the relative position of two features on different parts. The chain is a graphical representation of the transforms that affect the end dimension of interest.

This paper generalizes the chains used to quantitatively describe assemblies so that they can be used during concept design when there is too little information to be quantitative. The chains procedure preserves the structure and underlying assumptions of assembly modeling presented in Section 6 in order to preserve rigor and to create concept design results that can be carried over directly into detail design activities. The result is a way to estimate "integrality" during concept design when the detail needed for tolerance analysis and other traditional risk assessment activities is unavailable.

In addition to building on existing assembly modeling techniques, this paper also builds on the emerging method of Key Characteristics (KCs), as described in Section 3. [19, 20, 21] KCs are the physical attributes of a product whose variation will most influence the functions of the product and in turn most affect customer satisfaction, safety, and regulatory compliance. The chains method is aimed at diagramming conceptually the relationships between physical product elements so as to plan for successful "delivery" of a KC during concept design.

In this Section, we define a KC as a geometric attribute of the product that acts as a function carrier. Each KC is translated into one or more specific dimensional attributes, called Product Key Characteristics (PKCs) involving features on different parts. A chain represents how each PKC is achieved in an assembly, revealing dimensional relationships at several levels of the assembly process from modules to subassemblies to parts. The requirements on parts and fixtures at lower levels "flow down" from the PKCs along the chain and give rise to requirements called Assembly KCs (AKCs) and Part KCs. During concept design, enough of this flowdown must be specified and diagrammed to permit integration risks to be identified. If these concept phase activities are carried out systematically, they provide the assumption structure and relationships necessary for a seamless transition to quantitative formal assembly design and analysis, such as those described in [13].

Based on the above, we define a chain as "a graphical representation of dimensional relationships that affect a PKC, depicted on a hierarchy of the physical product elements, where each dimensional relationship can lie within a single physical element (a part, a component, a subassembly, etc.) or can lie between elements."

7.3. Outline of Chain Metrics Method

The chain metrics method lies within a larger process for an IPT. This process is illustrated in Figure 7-2. [3, 4] The IPT is assumed to consist of three main constituencies: design/performance, producibility, and strategy (technology acquisition and outsourcing). The process is designed to control the generation of concept architectures and the evaluation of their integration risk.

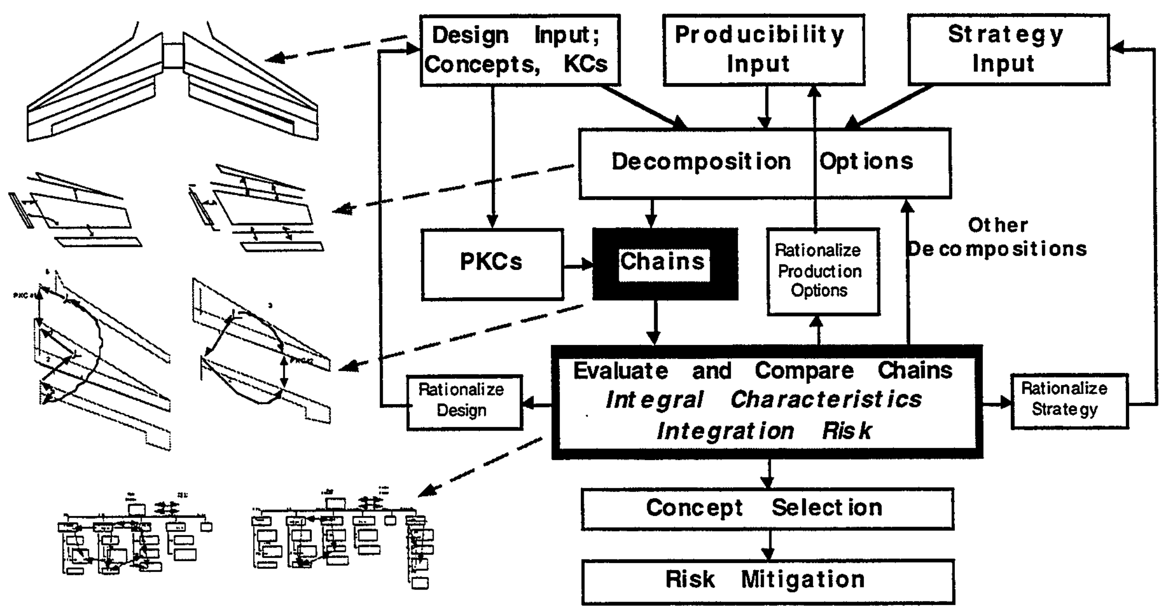

Figure 7-2. The complete method for concept design assessment of product architecture and integration risk based on chains.

We assume that some degree of functional analysis and decomposition has occurred. As discussed in [4, 10], much of design theory assumes or recommends that functional decomposition proceed down to the smallest functional elements. In practice, the IPT needs to resort to physical decompositions before functional decomposition has proceeded that far, in order to think clearly about producibility and outsourcing. The procedure outlined here works with an incomplete physical decomposition and assumes that the IPT will generate several of them. Each decomposition differs in how the functions are dispersed among the physical elements, which means that their architectures differ. The IPT wants to be able to evaluate them according to how they will be fabricated, assembled, supported in the field, outsourced to partners and suppliers, and delivered by new or existing technologies.

To accomplish the evaluation, the IPT carefully converts the KCs, which are common to all decompositions of a concept or derive from common customer requirements, into PKCs that are for the most part unique to each decomposition. Using the chains method, the team diagrams the delivery of each PKC onto the physical decomposition. A set of metrics is applied to the individual chains and then to the entire set of chains together, generating an overall metric of integrality and integration risk for the decomposition. Once this is done for several candidate decompositions, the team can compare them. The chains and metrics highlight the most risky areas of each decomposition, permitting the team to improve each concept from the point of view of design, production, and strategy. At the end of this analysis, a concept emerges, selected by, among other factors, attention to its integration risk and a plan for mitigating it. The selected concept is then carried ahead to detail design, which uses the chains to launch a formal definition of assemblies, features, dimensional control strategies, and process requirements.

7.4. The Chain Capture Procedure

This section describes the principles that serve as the basis for a chain capture procedure applicable in concept design along with a set of rules for representing chains graphically. The principles rely on the same basis as quantitative assembly modeling, as illustrated in Figure 6-1 and Figure 7-1, but cannot rely on the level of detail or completeness that a quantitative analysis uses because such detail is not available during concept design. This section reviews the basis for the quantitative analysis so that its essence can be transferred to the chain method. The information that can be reasonably expected to be available during concept design is then reviewed, from which constraining assumptions on any feasible chains method are derived. A

chain capture procedure that can operate within these constraints is then described along with rules for representing the chains graphically.

In order to explain the chain method, we need to define a "physical decomposition hierarchy." This is simply an assembly tree of the product, and is illustrated in Figure 7-3. The product is assembled by joining several modules, which are in turn made by joining several subassemblies. Some product decompositions are not hierarchical, but are flat and consist of a set of parts added one at a time to create the final product. Others are a mix of flat and hierarchical. The principles in this paper apply to all cases.

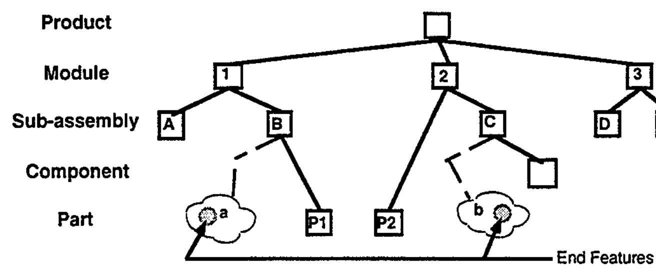

Figure 7-3. Illustration of a Product's Physical Decomposition Hierarchy. This particular decomposition is incomplete, as befits a concept design. Some portions are known down to the level of single parts while others end in undifferentiated subassemblies. Also shown are two end features buried in undefined components, which must be related accurately in space in order for a PKC to be delivered.

7.5. Information in Chains

7.5.1. Limited Information in Concept Design

A quantitative chain such as that in Figure 7-1 is described by two main types of information: a decomposition all the way down to individual parts, and knowledge about how the parts are connected to each other (by what are called assembly features) to form the assembly. From this information we can construct a quantitative model of how the end dimension is achieved, including a variation analysis. If the end dimension is a PKC, then the chain shows quantitatively how that function is mapped to the physical elements.

In concept design, the decomposition is incomplete because there usually is no time for a complete decomposition down to the last part and because such detail is not necessary for most concept design evaluations. The situation in Figure 7-3 is typical. If we require the chain method to have such detail, the method will not be used. The absence of detail is in fact an advantage that should not be sacrificed needlessly. It frees the designers to undo and revise their designs and delays commitment until it is necessary. Therefore the chain method must be able to deal with incomplete decompositions.

An incomplete decomposition lacks information about assembly features. Therefore we do not know the reference frames for individual parts and cannot duplicate the detailed locational information that is found in Figure 7-1. Therefore the chain method must be able to deal with incomplete knowledge of the reference frames.

At the same time, the method needs to obtain and preserve as much of the quantitative assembly information as possible. It will therefore seek to exploit any connective definitions available and encourage the designers to develop such information.

7.5.2. Necessary Information for the Chain Method

We require a chain that captures relationships between elements down to some predetermined level in the decomposition hierarchy that allows us to document the elements involved in achieving a dimensional relationship between two or more features. For example, in Figure 7-3, we require a chain complete down to the level of subassemblies that shows how the PKC between features 'a' and 'b' is achieved. We call the features related by a PKC *end features*. We assume that the designer can recognize which of the defined elements contain the end features 'a' and 'b'. We do not require that the designer know the parts that contain the end features, which are depicted by the clouds in Figure 7-3 to indicate that they have not been identified at this stage of the decomposition process.

We recognize that three reference frame relationships are needed:

- from module 1 to module 2, each of which contains one end feature
- from module 1 to sub-assembly B, which contains end feature 'a'
- from module 2 to sub-assembly C, which contains end feature 'b'.

We do not need to know what the parts are, what part or higher level assembly features will be used as the reference frames, or any of the geometry to recognize the structure of the chain that can be used during concept design. Now, we require a procedure to capture the chains systematically. The principles described in Section 7.6.1 make only two assumptions:

1. Decomposition candidates are available down to the level of interest; e.g. if we require understanding of how the KCs are mapped to sub-assemblies, each candidate decomposition includes the level of individual sub-assemblies (but not necessarily the levels below).
2. We know which elements in the hierarchy of a candidate decomposition contain one or more end features; e.g. which modules and sub-assemblies contain the end features in Figure 7-3.

7.6. Principles and Steps in the Chain Capture Procedure

The physical basis of chains is the fact that a physical element is located in space by some reference frame in that element, and that dimensional

relationships among the reference frames at several levels of the decomposition hierarchy and the end features determine how the end features are located relative to each other. The following describes this physical basis in five general principles, defines a chain capture procedure for a PKC with two end features, and illustrates the chain for the example in Figure 7-3.

7.6.1. Five Principles

We state six principles that generalize the physical basis of chains:

1. **Every physical element has a reference frame.**
2. **The PKC is *delivered* when the lowest element in the decomposition hierarchy has acquired (by fabrication and/or assembly) all the end features and is stable, so that the relative location of the end features remains intact through all subsequent levels of assembly. This lowest element is called the *root element.***
   Stability rule: The root element is stable if it is not compliant in degrees of freedom (DOFs) that are defined in the PKC.
3. **In documenting chains we leave the reference frame for each element denoted as "unassigned", i.e. no sub-element(s) is designated as that which contains the reference frame. In this way we do not make any assumptions about which parts or features are used as the reference frame.**
   Uniqueness rule: There can only be one reference frame for an element in each step in the assembly process.[14]
   Consistency rule: When an element's reference frame is assigned, it must be assigned the same for all chains that include that reference frame.
4. **A chain's *span* is established at the point at which the PKC is delivered. Span is defined in Section 7.8.**
5. **Chains initiate at a root link that defines the dimensional relationship between the elements containing end features that are assembled in the root element. The root link is discussed further below.**
6. **Chains contain branches that 1) initiate at the root, and 2) include links of dimensional relationships that extend down from the root link to the end features, passing through various elements at the different levels of the hierarchy and implying dimensional relationships between them.**

Each principle makes a specific point that allows us to create a chain capture procedure relevant to the information that is available in concept design. Principle #1 indicates that it does not matter if we do not know the exact assembly features that make up the reference frame of an element, there still must be a reference frame for every element. We say that the reference frame is "unassigned" but proceed knowing that one will be defined eventually. Principle #2 states that the only elements that affect a PKC are sub-elements of the root element. Principle #3 states that the procedure does not require that any decisions be made about reference frames; its rules guide us through how to apply any specific reference frame decisions that can be made. By allowing chains to be captured with unassigned reference frames,

[14] For example, if an element is located for assembly to another element, there is only one reference frame. If a third element is brought in, the same reference frame can be used or another can be selected. If all three are assembled in one step, there can only be one reference frame.

we permit different reference frame options to be investigated. Principle #4 states a character of chains called "span" that will be utilized in the metrics. Principles #5 and 6 characterize the structure of chains.

7.6.2. Procedure for Two End Feature PKCs

We can use these principles to define a procedure applicable to PKCs involving two end features, which is by far the most common type we have encountered to date. PKCs with more than two end features are also possible, and the procedure for these cases is discussed by [Cunningham 1998]. The two end feature procedure is:

1. **Identify the root element.**
2. **Document the "root link" in the chain: this is the link between the two elements, each of which contain one end feature, that are mated in the root element; we have identified two cases:**
   a) **the root link is the dimensional relationship between the *reference frames* of the two elements; this relationship is either delivered in a fixture or is a direct mate between features of the two elements.**
   b) **the root link is a dimensional relationship in a *third element* to which the two elements containing an end feature are assembled.**
3. **Document each of the two "branches" of the chain from the end of the root link to the end feature. Each branch systematically captures the relationships between reference frames in each level of the hierarchy. The final link in each branch runs from the lowest element defined that contains an end feature to the end feature.[15]**
4. **Apply any knowledge about specific reference frame assignment, or options that may be considered (this step interacts with the two cases in step 2).**

7.6.3. Chain Procedure Example

For the example in Figure 7-3, a chain can be captured just with the reference frame relationships listed in Section 7.5.2. Step 1 in the procedure involves recognizing that the final product is the root element because this is the lowest element in the hierarchy that contains all the end features. Step 2 involves documenting the root link between the two modules that contain end features, since each module contains one end feature and they are the two elements fully constrained relative to each other in the root element. Figure 7-4 shows two cases that match those discussed above. Figure 7-4a shows the root link if the dimensional relationship is between the reference frames of the two modules, and shows dashed lines that represent the branches of the chain that run down the through the modules (to be captured in the next step). Figure 7-4b shows the root link in module 3 if modules 1 and 2 are assembled to module 3, and dashed lines that represent the branches running *to* the modules and *then* down through them. In practice, options that match either of the two cases may be investigated, or one option may be recognized as preferable for the candidate decomposition. Step 3 involves capturing a branch in each module. In the example, there are two links in

[15] Detailed discussion of this step is in [4].

each branch: one from the module reference frame to the reference frame of the sub-assembly that contains the end feature, and a second from the sub-assembly reference frame to the end feature. Figure 7-5 illustrates these relationships in a graphical chain for the root link case of Figure 7-4a. Five dimensional relationships make up the chain:

1. between the two modules (the root link)
2. between the module 1 reference frame and the sub-assembly B reference frame[16]
3. between the sub-assembly B reference frame and end feature 1
4. between the module 2 reference frame and the sub-assembly C reference frame
5. between the sub-assembly C reference frame and the end feature 2

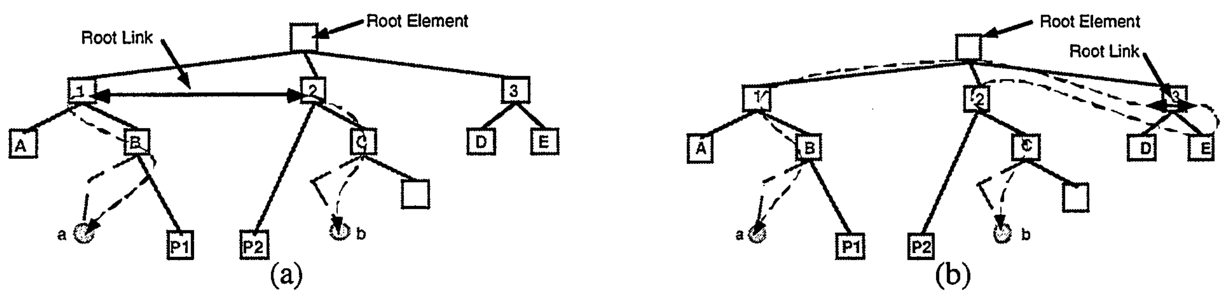

Figure 7-4. Two cases of the root link for the example in Figure 3, (a) between the reference frames of the two modules that contain an end feature, and (b) in a third element to which the other two modules are assembled.

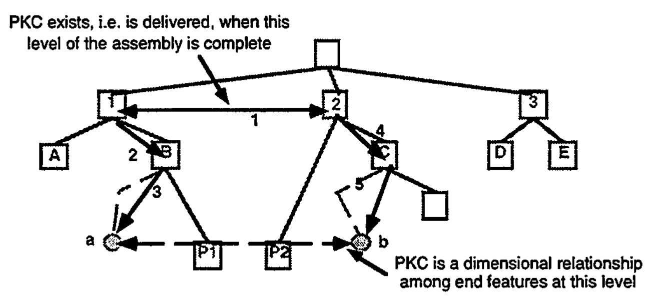

Figure 7-5. A chain representing the five dimensional relationships that deliver the PKC.

Note that Figure 7-5 clarifies two important aspects of KC delivery. A PKC is denoted as a relationship between a set of features at the level of parts. But, the PKC is not delivered, i.e. it does not exist in the assembled product, until all the links are achieved, including those at higher levels in the hierarchy that correspond to downstream steps in the assembly process. The chain also identifies each physical element that plays a role in achieving the PKC.

[16] Again in keeping with Principle #3, we do not assume that the module and sub-assembly reference frames are the same. If they are eventually assigned to the same features, then the two reference frames will be the same and this link will disappear. This is a downstream decision that will affect many PKCs in a real product.

7.6.4. Rules for the Graphical Chain Representation

The simple example above also demonstrates three rules for graphical chain representation:

1. **Root Link Representation: a root link is represented as a double headed arrow**
2. **PKC Representation: the PKC is represented as a dashed double-headed arrow**
3. **Branch Link Representation: all links in each branch are depicted as arrows that point away from the root link and toward the PKC.**

7.7. Aircraft Example

The utility of the chain capture procedure can be illustrated in the context of an aircraft structure example. The product explored below is the horizontal stabilizer assembly shown in Figure 7-6, which is described by Cunningham et al [22], where the assembly process for one sub-assembly was developed. The assembly is built in

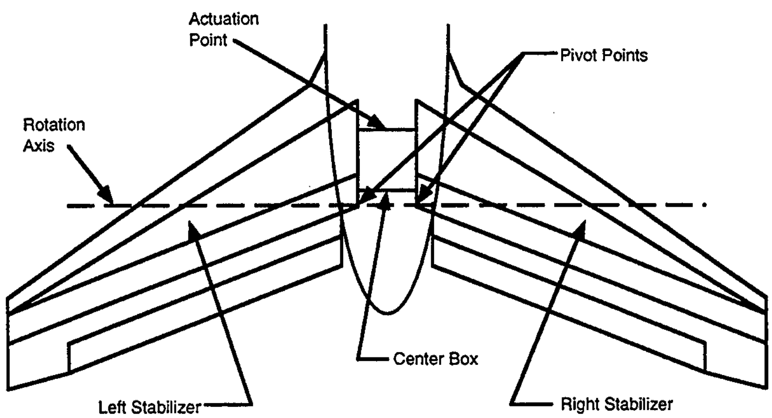

Figure 7-6. Three modules of the Horizontal Stabilizer, the axis of rotation, and the actuation and pivot points.

three modules: left and right stabilizers and a center box. Note that this is an example where all parts of the assembly are known; i.e. the design and decomposition were complete at the time of the study. Our investigation here considers different decompositions of the product and does not require all the available information about the actual parts. While this does not precisely reflect the context of concept design, the example proves a larger point about what can and must be accomplished during concept design in order for an IPT to control the architecture of the product. Our method has been tested and documented on a real concept design case study to ensure its applicability [3, 4, 23]. This case is discussed further in Section 8.

The following describes the assembly, the current decomposition, two PKCs, the chains and resulting architecture insight for the current decomposition, and three alternate decompositions with different

architectures. Section 7.8 then introduces metrics that support a more formal analysis of each alternate decomposition.

7.7.1. Assembly Description

Each left or right stabilizer is in effect a box beam structure (called the main torque box) with a forward and aft spar running the full length, stiffened upper and lower skins that act as the top and bottom of the box, several ribs along the length, and a heavy inboard structure that connects the spars, the inner-most rib, and the upper and lower skins, as shown in Figure 7-7a (without the upper skin). Figure 7-7b shows the configuration of the inboard structure that includes a forward and aft "end fitting" and an upper and lower "plus chord" (described further below). The main torque box sustains the bulk of the differential loads on the upper and lower

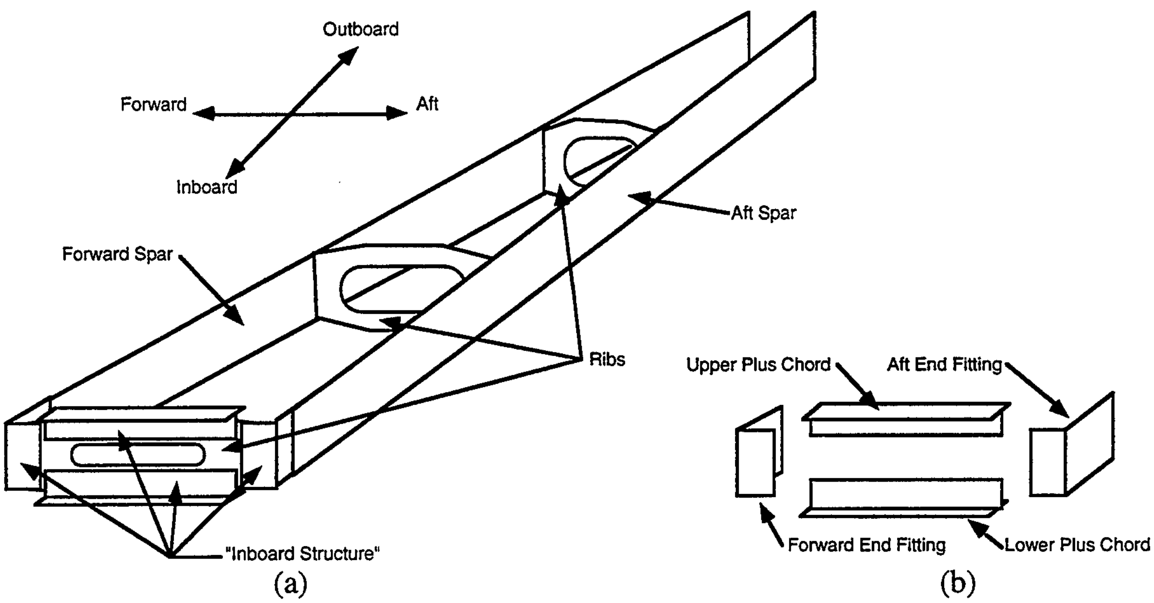

Figure 7-7. The two spars, ribs, and the "inboard structure" - detailed in (b) - make up the main torque box with the upper and lower skins that are not shown here.

surfaces and torsion loads along the length of the stabilizer. The section forward of the main torque box carries some loads also but mainly creates an aerodynamic shape, while the section aft completes the airfoil shape and includes the hinged section called the elevator whose position can be adjusted to change the airfoil shape.

7.7.2. Current Decomposition

Figure 7-8 shows an exploded view of the right stabilizer as it is currently decomposed. There are four sub-assemblies:

- Forward Torque Box (FTB), including the *forward spar and end fitting*

- Fixed Trailing Edge (FTE), including the *aft spar and end fitting*
- Upper Skin, including the *upper plus chord*
- Lower Skin, including the *lower plus chord*

The ribs, each installed individually, are considered as a group as a fifth sub-assembly in this analysis.

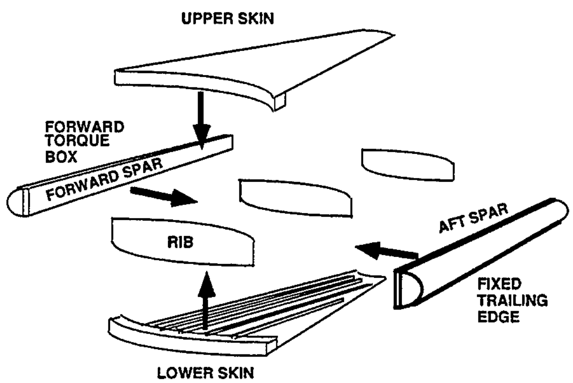

Figure 7-8. Exploded view of sub-assemblies making up the right horizontal stabilizer.

Figure 7-9 shows the physical hierarchy of the current decomposition, including the detail parts that will be part of the discussion below. The third layer of the

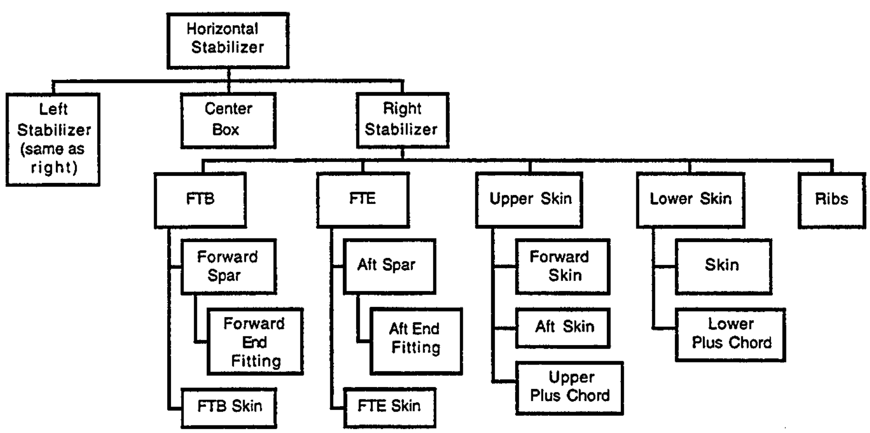

Figure 7-9. Horizontal Stabilizer hierarchy in the current decomposition.

decomposition is a group of parts and components; the spars and ribs are themselves assemblies of a few parts so they are "components." Note that the main torque box is not built as a sub-assembly, but is parsed out to the five sub-assemblies and is completed when these five-sub-assemblies are assembled as a module. Also note that the upper skin sub-assembly has a skin broken into two parts called for "forward" and "aft" skins. In the discussion that follows, these can be thought of as a single skin but we will continue to use the names that distinguish the two parts.

7.7.3. PKCs

The principal requirements for this structure are to carry the aerodynamic loads while minimizing the drag it creates so overall system efficiency is maximized. Two PKCs are considered in the discussion below, while a more complete set discussed in [4, 22] is discussed in the context of the metrics illustration in Section 7.8. The two PKCs are:

PKC #1: alignment of the upper plus chord forward edge to the forward end fitting (Figure 7-10a).
PKC #2: gap between the aft skin and FTE skin (Figure 7-10b).

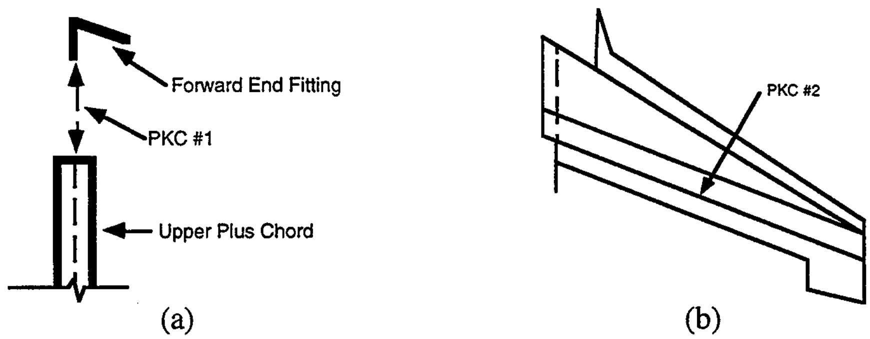

Figure 7-10. (a) PKC #1 and (b) PKC #2.

7.7.4. Chains for Current Decomposition

Figure 7-11 shows a chain representation of how PKC #1 is delivered in the current decomposition. This chain representation is depicted on a sketch of three sub-assemblies: the FTB, FTE, and upper skin. The PKC is delivered at the module level, when the FTB and upper skin are mated. The root link lies in the FTE because, in the current assembly process, both the upper skin and FTB are referenced to locations in the FTE. The upper skin is referenced directly to features on the FTE (which can be used to specifically define link 2). The FTB is referenced to the FTE in a fixture (link 4) where the FTB, FTE, and upper skin are assembled. In fact, the only reference frame information that is required is the assumption that the two sub-assemblies that contain the end features are referenced to locations in a third element. This illustrates case b of step 2 in the chain procedure where the root link lies in a third element. None of the specific knowledge about the assembly process is needed to depict this chain. Links 2-5 in the two branches are similar to those encountered in the basic problem of Section 7.4. While the end features lie in *two* sub-assemblies, we find that the PKC is affected by dimensions within each of the *three* sub-assemblies and in two interconnections.

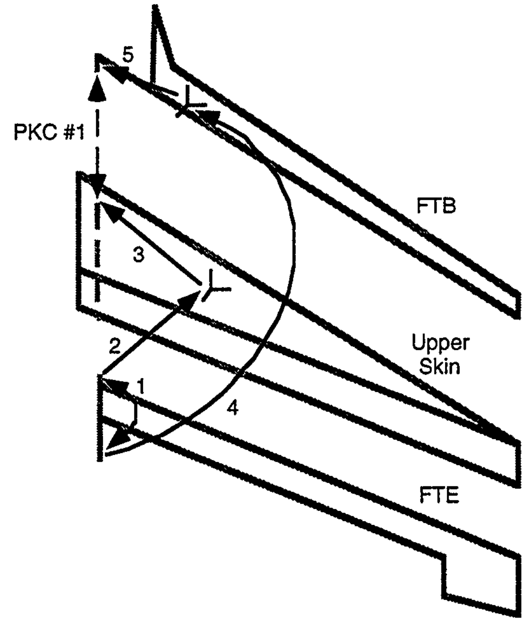

Figure 7-11. Chain to deliver PKC #1 in the current decomposition.

Figure 7-12 shows a chain representation of how PKC #2 is delivered. This PKC is also delivered at the module level, when the FTE and upper skin are mated. The root link lies between the upper skin and FTE.

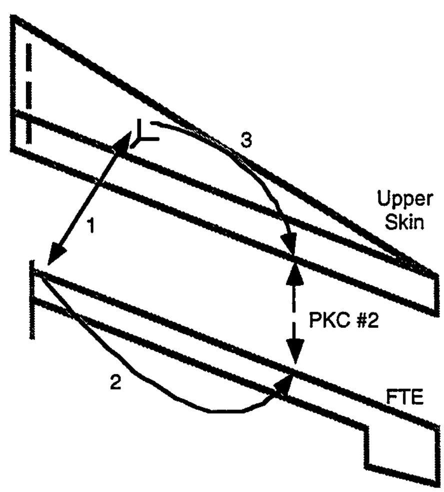

Figure 7-12. Chain to deliver PKC #2 in the current decomposition.

It is important to note that we see an indication of "coupling" between the two PKCs. That is, the two chains are shared by the same elements and share some common links between elements. If there are more PKCs than there are DOFs available to deliver the PKCs, we say that the KCs are in "conflict" because they can not be achieved independently. When PKCs conflict, a disturbance in one chain can set off a disturbance in another chain. In fact, this is the case with these two PKCs, and is the basis for selecting a particular upper skin assembly process by described in [22]. We see here that

coupling of the PKCs can be recognized with a high level chain analysis before there is substantial detail. The three alternate decompositions discussed below are shown to decouple these two PKCs. In Section 7.8, we discuss how coupling is a measure of the integration in the product architecture that can be recognized in concept design.

Figure 7-13 shows how the chains can be depicted on a hierarchy of the right stabilizer. This hierarchical view of the decomposition, along with sketches of some of the elements, are the types of views that concept design typically provides. These views allow all members of the team to relate a particular physical element to a PKC, and hence to a function. This view also shows the coupling, where both PKCs are affected by the interface between the upper skin and FTE, and both chains are shared in the FTE and upper skin. We will use this view below to contrast the chains in the three alternate decompositions.

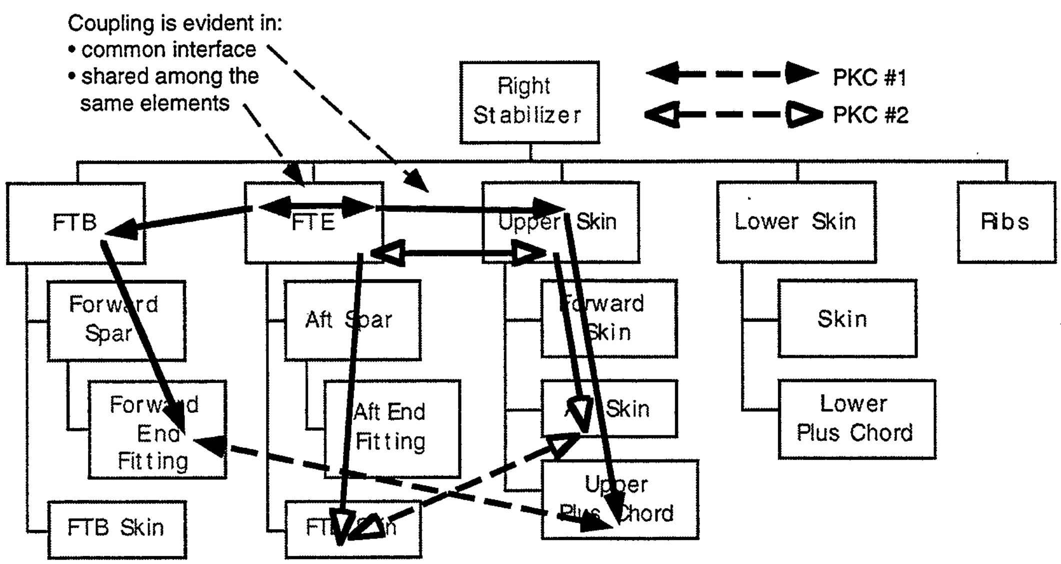

Figure 7-13. Chains depicted on the hierarchy of the current decomposition.

7.7.5. Three Alternate Decompositions

Three alternate decompositions were found to alter the mapping of the two PKCs and the coupling of the two PKCs. The first two are unique, and the third is a hybrid of the other two.

7.7.5.1. Alternate #1: Main Torque Box Sub-assembly

The main torque box sub-assembly alternate decomposition includes three sub-assemblies, an FTB, FTE, and Main Torque Box (MTB) that contains the spars and end fittings allocated to the FTB and FTE in the current decomposition. The MTB has five components as shown in Figure 7-14: the

forward spar, aft spar, upper skin, lower skin, and the ribs. PKC #1 is now delivered in the MTB sub-assembly, as depicted in Figure 5-14 where all links are found just in the sub-assembly as opposed to in multiple sub-assemblies. PKC #2 is still delivered at the module level because the chain crosses sub-assemblies. There is the opportunity to decouple the two PKCs because there are no shared interfaces among elements.

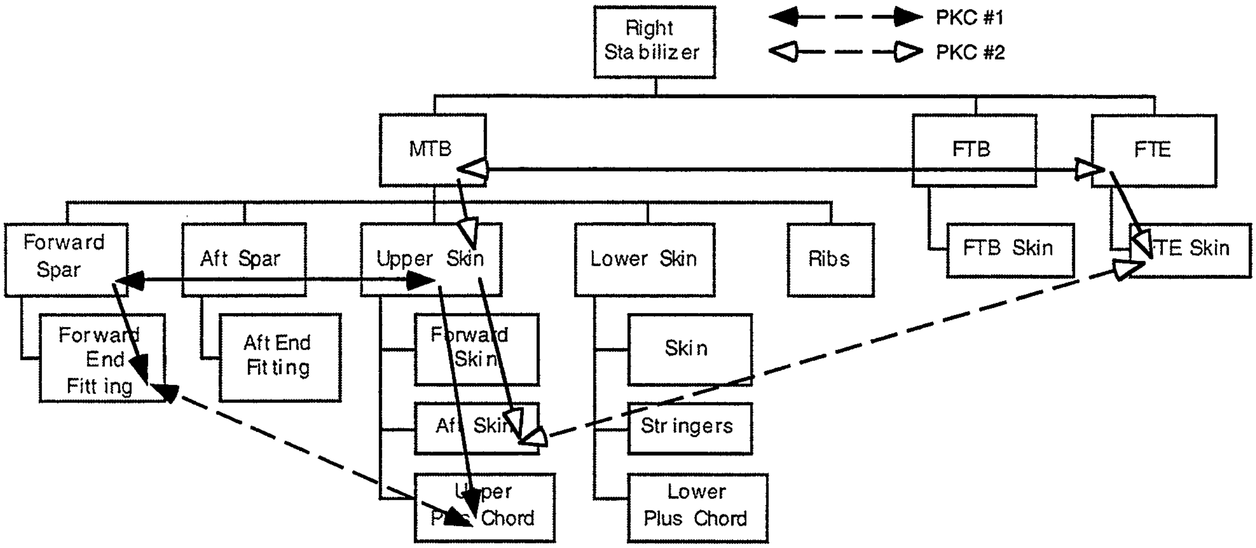

Figure 7-14. Hierarchy and chains of alternate decomposition #1.

Several issues must be considered with this decomposition:

- if the upper skin was already on the critical path of assembly, the new decomposition may grow the cycle time for the entire assembly because additional work that was previously done in parallel has been transferred to the MTB sub-assembly and onto the critical path
- the FTB and FTE may not be stable sub-assemblies without the spars
- significantly different tooling would be required when compared with the current decomposition of the right stabilizer, and an additional complex tool for building the MTB, on the order of the scale of the module assembly fixture, would have to be added; non-recurring cost would increase
- no design change is evident, but different joints would be made between the spars and FTE and FTB, than are currently made at right stabilizer assembly; these joints would require analysis for accessibility.

7.7.5.2. Alternate #2: Pivot Rib Sub-assembly

The "pivot rib sub-assembly" alternate decomposition includes a sixth sub-assembly in addition to the FTB, FTE, and upper skin, lower skin, and the ribs. The pivot rib sub-assembly contains the end fittings and two plus chords, the four parts of the inboard structure allocated to the other sub-assemblies in the other decompositions. The hierarchy is shown in Figure 7-15. PKC #1 is delivered in a single sub-assembly, while PKC #2 is still delivered at the module level. There is no coupling of the PKCs.

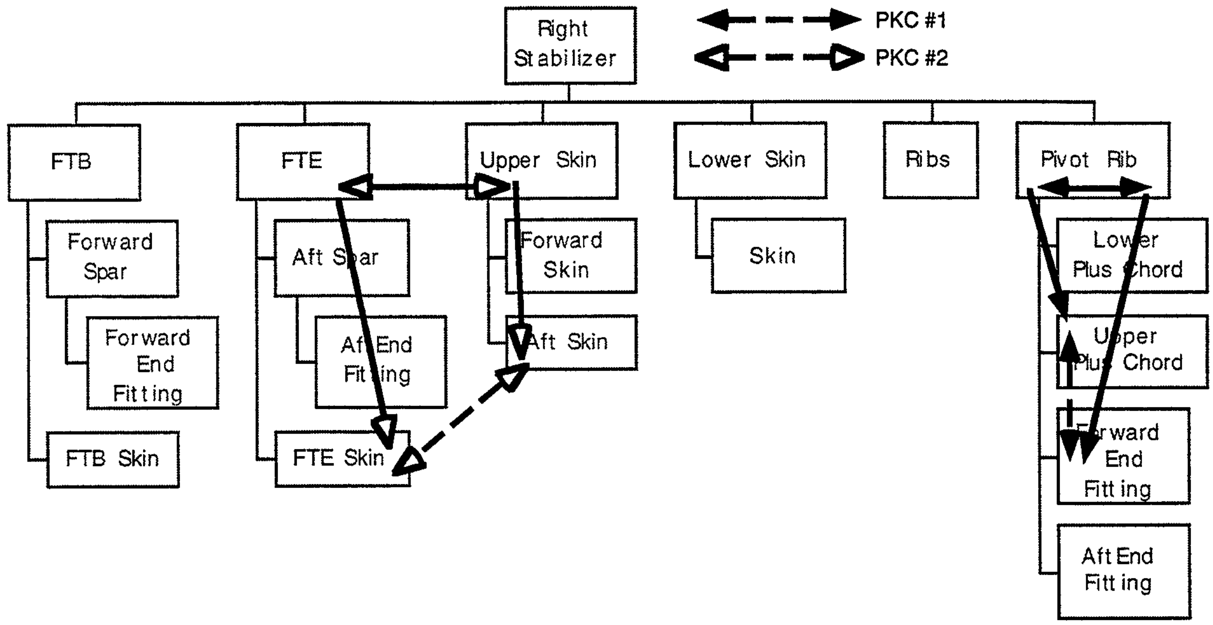

Figure 7-15. Hierarchy and chains of alternate decomposition #2.

Again, several issues must be considered with this decomposition:

- The most critical design issue associated with this decomposition is the difficulty of making the plus chord to upper skin joint. The joint as designed in the existing configuration would be inaccessible and the fixture as currently designed could not sustain the forces encountered in assembly. The joint would have to be redesigned.
- The mate of the end fittings to the spars could also be difficult. While these mates were not identified as KCs in our study of the assembly, these also lie on important load paths and may require substantial attention to correct any fit-up problems created by the alternate decomposition.
- Unlike alternate #1, the stability of all the assemblies is maintained.

7.7.5.3. Alternate #3: Hybrid of Alternatives 1 and 2

A hybrid of the two alternatives would have the pivot rib as a component within the MTB sub-assembly. This decomposition further simplifies the architecture by accomplishing PKC #1 in the single pivot rib component. In fact no KCs would be delivered in the MTB, which simplifies the process and fixture construction. This hybrid is the most simple from a KC perspective but carries with it the advantages and disadvantages of the two alternates. Both the disadvantage of the difficult joint in alternate #2 would need to be addressed, as would the unstable sub-assembly problem of alternate #1.

7.8. Metrics

When the problem involves only one or a few PKCs, like that described in Section 5, a side by side pictorial comparison of the chains indicates much

about the architecture and integration risk. If Figure 7-13-, 14, and 15 are placed side by side, it is clear that alternates 1 and 2 simplify the delivery of PKCs and also decouple them. This pictorial character of chains enables it to communicate among the many disciplines in an IPT. Chains like this can be populated with the suppliers, processes, and specific dimensions that affect each chain as this information becomes available to coordinate among the many tasks in product development.

In fact, any real product will have more than one or a few PKCs, and the pictorial capability of chains begins to break down when more than a few are depicted in a single image. So in practice, additional means are needed to represent many chains and to assess them systematically to achieve an aggregate comparison of candidate concepts and decompositions. In the case of the horizontal stabilizer assembly, there are in fact at least 6 dimensional relationships that must be considered at the level of just the right stabilizer module, and more if the entire stabilizer is considered. We have developed a matrix tool to assist in the representation of many chains, and metrics to support an evaluation of many chains [4, 24].

Our work has investigated two types of metrics. The first type reveals the integral characteristics. The second type is used to estimate the integration risk associated with these integral characteristics. After the IPT follows the chain capture procedure, it uses these metrics to systematically evaluate the chains to compare the candidate concepts and decompositions. These metrics are qualitative in nature, but lead an IPT toward a quantitative analysis by indicating the highest risk characteristics that warrant the resources required to perform a quantitative analysis [23]. This section briefly describes these metrics, which are discussed in greater detail in [3, 4].

7.8.1. Chain Structure Metrics

The Mapping Metric measures two attributes of the chain: its *span* and its *height*. The span is the highest level in the hierarchy occupied by a link in the chain. The span is one level below the root element, because the span is defined as the highest level with relationship among elements, and root element is the lowest element that contains all the end features. The metric is larger if the hierarchy level is higher, and indicates a higher degree of integrality because of the implied larger number of elements and their designers, suppliers, assemblers, inspectors, and so on, involved in delivering the KC at the root. Figure 7-16 shows two cases with the same span, where the root element is the highest level of the hierarchy. The height is the vertical distance in the hierarchy occupied by the chain. We assume that the bottom is always at the part level even if parts have not yet been identified. Larger height indicates more integrality due to longer communication links along the chain and different levels of perspective among the communicators. The height may differ in different branches of the chain, so

we take the maximum level to measure the level of integrality. In order to measure the height, something must be assumed about frames in each branch of the chain. This can take the form of different options or specific reference frame assignments. Without any reference frame assumptions, only the span can be measured and the height should be assumed as the maximum. Figure 7-16 shows how two cases with the same span can have different height. Table 7-1 shows how to calculate the mapping metric from the span and height.

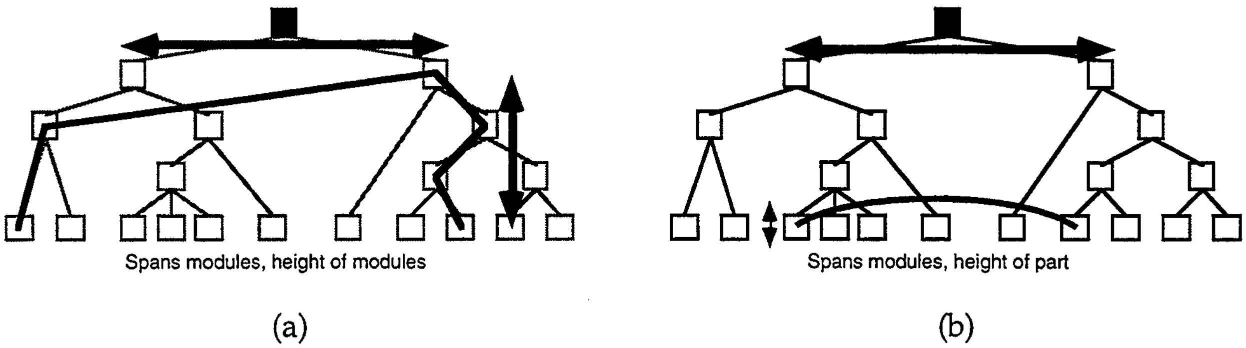

Figure 7-16. Illustration of Span and Height with two chains depicted on the same physical hierarchy. In both cases the root element is the highest level of the hierarchy, so the span is the same. But, the height can differ.

		SPAN		
		Module	Sub-assy	Component /Part
HEIGHT	Module	High	n/a	n/a
	Sub-assy	Medium	Medium	n/a
	Component /Part	Low	Low	Low

Table 7-1. Calculation of Mapping Metric of a Chain Based on its Span and Height (n/a means not applicable: span ≥ height)

The Coupling Metric compares the mapping metrics of two chains that share at least one link. This metric allows us to increase the integrality of an otherwise modular chain if it is coupled to a chain with a high mapping metric (indicating that it is integral). The Coupling Metric (CM) of either chain is calculated from their respective Mapping Metrics (MM) as follows:

CM(Chain 1 or Chain 2) = max (MM for Chain 1; MM for Chain 2)

The Critical Path Metric measures the combination of a chain's integrality and its potential impact on production span time. A critical path in assembly usually appears in the decomposition hierarchy as a set of elements occupying one branch of the tree. The critical path metric is calculated by counting how many links of a KC chain pass through elements on the critical

path. In Figure 7-17, there are three such elements. More such elements indicate a higher value of the metric and add integrality to a chain.

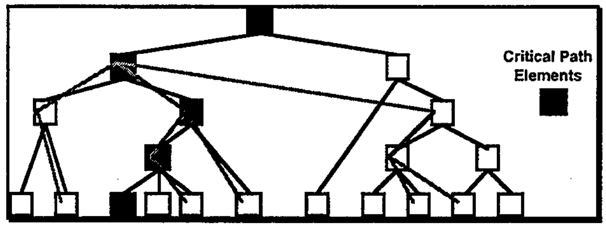

Figure 7-17. Calculation of the Critical Path Metric (in this case, 3)

7.8.2. Combined Chain Structure Measure

These three metrics are combined to create an overall Chain Structure metric for each KC. The details are in [4]. What is important here is to understand that any monotone method for combining the metrics will be sufficient to guide the IPT toward identifying chains that demand further attention. This approach is in the tradition of classification and coding, which underlies similar design evaluation methods such as design for assembly.

7.8.3. Integration Risk Metrics

A high value of the chain structure metric does not guarantee integration risk. For this reason, we have developed a second set of metrics that highlight particularly risky technical, managerial, and organizational situations. These metrics are:

- number of links in a chain (a technical complexity measure)

- number of organizational boundaries crossed by a chain (an organizational complexity measure)

- lack of robustness or novelty of technologies or processes relied on to deliver links in the chain, or degree of dependence on suppliers for such technologies (a strategy and capability impact measure)

A higher number of links in a chain indicates more sources of error. A higher number of organizational boundaries crossed by a chain additional interfaces that must be managed, each a source of error. A higher number of risky technologies or technologies not controlled by the final assembler indicates uncertainties about performance in time, cost, or quality. In [25, 26] risks associated with outsourcing are categorized. Higher risk is associated with outsourcing integral items or those whose chains are coupled to other chains, especially when the source controls the key knowledge needed to deliver the chain.

7.8.4. Combined Integration Risk

The combined integration risk of a chain is calculated by combining the chain structure score and the integration risk score. See [4] for details. Again, the particular choice of scoring method is immaterial as long as it is monotone.

7.9. Illustration of the Chain Metrics Applied to the Aircraft Example

The horizontal stabilizer current and alternate decompositions can be compared systematically with the metrics. This section describes how to apply the metrics to the current decomposition, then summarizes a comparison with each alternative.

The right stabilizer module is the root element for both PKCs in the current decomposition. Both PKCs span sub-assemblies. This is indicated in Figure 7-13 by the links that cross the sub-assemblies. The integrality of each PKC will be found in the second column of Table 7-1. In order to score the height, we require additional information about the reference frames. There are two possibilities in the second column of Table 7-1. The height can only be at the component/part level if the reference frame for the sub-assembly containing the end feature is assigned to the same part or component. Take as an example PKC #1 and the branch of the chain in the upper skin. The upper skin has no components, so we can only consider the parts. To have a height at the level of parts, the reference frame used to locate the upper skin relative to the other reference frames must be assigned to the plus chord, which is the part that contains the end feature. This is not the case because the reference frame in the existing process is assigned to the aft skin. Therefore, the height is at the level of the sub-assembly, where the plus chord and aft skin are mated into the upper skin sub-assembly. Therefore, PKC #1 is scored as MM=medium (span=s-a, height=s-a). PKC #2 is also scored as MM=medium because the height of the branch in the FTE is at the sub-assembly level.

The two PKCs are coupled, and are both scored MM=medium, therefore both are scored CM=medium. Assume the assembly critical path is the FTE sub-assembly and right stabilizer module. Both chains are on the critical path in both levels of the hierarchy. Therefore, both are scored high on the critical path metric.[17]

Both PKCs in the current decomposition are revealed to be integral when a combined measure of the three metrics is applied.

[17] Note that the chain for PKC #1 has links in all three sub-assemblies, and is therefore on the critical path in both levels of the hierarchy no matter which sub-assembly lies on the critical path.

Table 7-2 and Table 7-3 show a comparison of the current decomposition and the three alternates for PKCs 1 and 2, respectively. The bottom row of each table states whether the combined measure indicates integrality. PKC #1 is not revealed to be integral in any of the three alternates. In all three alternates, PKC #1 scores MM=low because it is delivered in a single sub-assembly or component, and CM=n/c (not coupled). In the case of alternate #1, PKC #1 is scored medium on the critical path metric because the MTB sub-assembly, the root element for the PKC in this decomposition, is on the critical path. In alternates 2 and 3, PKC #1 scores low on the critical path because it is not on the critical path. PKC #2 is integral in all cases because it scores MM=medium and lies on the critical path in two levels of the hierarchy.

Metric	Current	Alternate 1	Alternate 2	Alternate 3
(span)	s-a	c	c	c
(height)	s-a	c	c	c
MM	medium	low	low	low
CM	medium	n/c	n/c	n/c
Crit. Path	high	medium	low	low
Combined	integral			

Table 7-2. Integrality Rating for PKC #1 in Four Candidate Horizontal Stabilizer Decompositions

Metric	Current	Alternate 1	Alternate 2	Alternate 3
(span)	s-a	s-a	s-a	s-a
(height)	s-a	s-a	s-a	s-a
MM	medium	medium	medium	medium
CM	medium	n/c	n/c	n/c
Crit. Path	high	high	high	high
Combined	integral	integral	integral	integral

Table 7-3. Integrality Rating for PKC #2 in Four Candidate Horizontal Stabilizer Decompositions

The integration risk metrics are now applied to each integral characteristic. In each of the candidate decompositions, PKC #2 exhibits high integration risk because it is delivered in multiple sub-assemblies made by different suppliers, and one of these, at the time of this study, was planned to be converted to new fabrication and assembly technologies. Therefore PKC #2 proved to be an integral, high risk KC in any option for this design concept. PKC #1 is also exhibits high integration risk in the current decomposition for the same reasons. The choice of decomposition has the opportunity to reduce the level of integrality in PKC #1, and with it the integration risk.

In the full investigation of this example, there are unique architectures and integration risks for each of the candidates(see [4]). There are six KCs to be

considered. In the current decomposition there are three coupled pairs. In all three alternates there is one coupled pair. This is indicative of what will be faced in practice. It is unlikely that all the integrality can be eliminated from a design concept that has some inherent integrality. Instead, some level of integrality, and integration risk, will be present. The example with 2 PKCs considered shows how the metrics provide a more formal process to reveal what can be intuitively observed when Figure 7-13, 14, and 15 are placed side-by-side. The full comparison shows how the formal analysis provides the necessary insight when the complexity exceeds the level where a simple side-by-side comparison is possible.

7.10. Conclusions

This Section makes two contributions. First, it presents a chain capture method and metrics applicable to concept design that permits a cross-functional IPT to identify integration risk based on limited information. The procedure generalizes existing rigorous methods for modeling assemblies, and in doing so accomplishes two additional results. First, the chain method is systematic and repeatable. Second, the results can be carried forward directly to detail design and used as the baseline for definition of assemblies, assembly features, tooling, process capability, and tolerance design for the ultimate delivery of the KCs. Traceability back to the original concept phase assumptions is thereby established, increasing the coherence of the whole design process.

The second contribution is to enrich existing design theory by directly addressing the contending attractions of integrality and modularity that arise in realistic product development situations. It does this by providing a specific method for achieving, as closely as is realistic, the ideals of independence of design parameters, modularity, simplicity of interfaces, and so on, which are advocated in design theory. An IPT can use this method to consciously plan a product's architecture and decomposition with informed attention to integration risk at the only time when the opportunity exists. The metrics developed address a larger domain of constituencies (performance, producibility, and technology/outsourcing) than previous design theory has done, and they do so in a way that these different constituencies can all understand.

7.11. References

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8. The Datum Flow Chain[18]

Assembly is the point in the product cycle where parts from disparate sources come together and the product first comes to life. Fit-up problems are often discovered during final assembly when trying to put these parts and sub-assemblies together. Finding the source of these fit-up problems is a very difficult and time-consuming task, and most of the time the exact causes cannot be identified. The time and cost involved to make engineering changes, in-process adjustments, etc. to fix these problems increase rapidly as the product development process evolves. Early anticipation and avoidance of these problems can have a huge impact in reducing the product development time, cost, and production fit-up problems, and can improve final product quality.

Many fit-up problems occur due to a part-centric approach to product design that ignores assembly and system issues. It is common to view assembly as a process that merely fastens parts together. The assembly process should be viewed as a proxy for a wide range of decisions, events, and relationships between different stages of the product development process. Assembly is really chaining together of dimensional relationships and constraints. The success of these chains determines the success of the product's quality from an assembly point of view. The goal of assembly modeling is to permit these chains to be defined first, and followed by design of individual parts. We propose a concept called the "Datum Flow Chain" (DFC) to implement this approach to assembly modeling.

This method is able to capture the locational, constraint, and dimensional logic of an assembly in a skeleton that is like an electric circuit diagram. It has a dimensional root or main datum (like electrical ground) and each part has a defined location relative to the root, analogous to the voltage of each node in a circuit. This skeleton is capable of representing these three essential features of an assembly using one common mathematical representation, the 4x4 transform matrix:

- location responsibility of one part or fixture for another
- constraint of each part (up to 6 degrees of freedom)
- variation

Current CAD systems provide rudimentary assembly modeling capabilities once part geometry exists, but these capabilities basically simulate an assembly drawing. Most often the dimensional relations that are explicitly

[18] This section is adapted from [Mantripragada and Whitney]

defined to build an assembly model in CAD are those most convenient to construct the CAD model and are not necessarily the ones that need to be controlled for proper functioning of the assembly. What is missing is a way to represent and display the designer's strategy for locating the parts with respect to each other, which amounts to the underlying structure of dimensional references. The DFC is intended to capture this logic.

Ideally, the design of a complex assembly starts by a general description of the top level design requirements (key characteristics, KCs [1]) for the whole assembly. These requirements are then systematically formalized and flowed down to sub-assemblies and finally down to individual parts. During these early stages of design, the following major elements of the design process have to be considered:

1. Systematically relate the identified KCs to important datums on assemblies, parts, and fixtures at the various assembly levels

2. Design consistent dimensional and tolerance relationships (locating schemes) among elements of an assembly so as to deliver these KC relationships

3. Identify assembly procedures that best deliver the KCs repeatedly without driving the costs too high.

This paper is an extension of the work introduced by the authors in [2] and presents techniques that formalize this approach to designing assemblies. Section 8.2 provides background on some of the terms and concepts used in the paper. The concept of the DFC and its properties and relationship to KCs are described in Section 8.3. Section 8.4 identifies two types of assemblies that require different modeling methods because they are assembled by totally different means. The DFC provides for a structured method of planning out the assembly procedures which is described in Section 8.5. Section 8.6 presents analysis techniques to choose between alternate DFCs. Section 8.7 summarizes the modeling approach and presents directions for future research.

8.1. Background

Assemblies have been modeled systematically by Lee and Gossard [3], Sodhi et al [4], Srikanth and Turner [5], among others. Such methods are intended to capture relative part location and function, and enable linkage of design to functional analysis methods like kinematics, dynamics, and in some cases tolerances. Gui and Mantyla [6] have attempted to apply a function-oriented structure modeling to visualize assemblies and represent them in varying levels of detail. Other researchers have studied methods to generate assembly sequences [Defazio and Whitney [7], Ko and Lee [8], Wilson [9]] for the assembly starting from the descriptions of the parts constituting the assembly. There has not been much effort to identify assembly sequences at a

concept stage where the geometry of the parts is not certain yet and use them to influence the design of the assembly.

Top-down design emphasizes the shift in focus from managing individual part design to managing the design in terms of mechanical "interfaces" between parts. Smith [10] proposes eliminating or at least minimizing critical interfaces in the structural assembly rather than part-count reduction as a means of reducing costs. He emphasizes that at every location in the assembly structure, there should only be one controlling element that defines location, and everything else should be designed to "drape to fit." This is similar to the idea of mates and contacts introduced by Mantripragada et al [2]. Muske [11] describes a top-down design methodology to systematically translate key characteristics of 747 fuselage sections to critical features on parts and choose consistent assembly and fabrication methods. No computer or conceptual tools to support these processes are described.

Shah et al [12] proposed an attributed graph model to interactively allocate tolerances, perform tolerance analysis and validate dimensioning and tolerancing scheme at a part level. This model defines chains of dimensional relationships between different features on a part and can be used to detect over and under dimensioning of parts. The DFC is an extension of this idea to an assembly level where dimensional chains that define part-part relations are used as a basis to control the design.

8.2. Datum flow chain

8.2.1. The concept

An assembly is characterized by a set of key characteristics (KCs) that it has to deliver upon final assembly. These are assembly level dimensions relating a datum or feature on one part to that on another part in the assembly. An example KC is the size and straightness of the gap between a car hood and fender. Typically, such KCs are achieved (or delivered) when several different parts are made and assembled correctly. The dimensional relations between parts are defined at their mating points (features).

Not all of the joints in an assembly transfer dimensional constraint, and it is essential to distinguish the ones that do from the ones that are redundant location-wise and merely provide support or strength. We define the joints that establish dimensional relationships between parts as ***"mates,"*** while joints that merely support and fasten the part once it is located are called ***"contacts"***. Hence mates are directly associated with the KCs for the assembly as they define the resulting assembly dimensions. The mates must be fastened first and only then can the contacts be fastened.

Explicit identification and definition of the mates in the assembly is an integral part of assembly design and is a pre-requisite to assembly process planning and variation stackup analysis. The choice of which joints will be ***mates*** and which ones will be ***contacts*** is made by the designer at the conceptual design stage. If these distinctions can be expressed carefully and mathematically, then we can construct directed graph representations for dimensional transfer from mate to mate in a declarative way, providing a basis for synthesizing tolerance achievement. We call this directed graph of *mates* the ***Datum flow chain*** *(DFC)* [2]. In some assemblies, *mates* are accomplished in whole or partly by supporting fixtures that have to be included in the DFC.

8.2.2. Assumptions

The following assumptions are made to model the assembly process using a DFC:

1. All parts in the assembly are assumed rigid. Hence each part is completely located once its position and orientation in the three dimensional space are determined.

2. Each assembly operation completely locates the part being assembled with respect to existing parts in the assembly or an assembly fixture. Only after the part is completely located is it fastened to the remaining parts in the assembly.

8.2.3. Properties of a DFC

A datum flow chain is a directed acyclic graphical representation of an assembly with nodes representing the parts and arcs representing *mates* between them [2]. Every node represents a part or a fixture and every arc transfers dimensional constraint from the node at the tail to that at the head. Loops or cycles in a DFC would mean that a part locates itself once the entire cycle is traversed, and hence are not permitted. Every arc constrains certain degrees of freedom depending upon the type of mating conditions it represents. The sum of the degrees of freedom constrained by all the incoming arcs to a node (called the in-degree) in a DFC should be equal to six unless there are some kinematic properties in the assembly or designed mating conditions such as slip joints which can accommodate some amount of pre-determined motion. Each arc has an associated 4x4 transformation matrix that represents mathematically how the part at the head of the arc is located with respect to the part at the tail of the arc. A typical DFC has only one root node that has no arcs directed towards it, which represents the point from which the assembly process begins. This could either be the base part or a fixture.

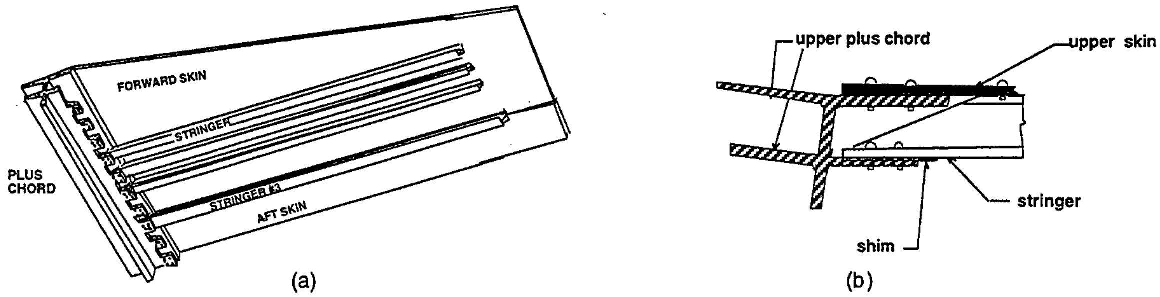


Figure 8-1: Example assembly (Airplane horizontal stabilizer upper skin assembly). This assembly is part of the horizontal stablizer shown in Figure 7-8.

Consider the aircraft horizontal stabilizer skin assembly shown in Figure 8-1. It consists of four main parts: Plus-chord, Aft-skin, Fwd-skin and 11 stringers. Stringer 3 is called the splice stringer because it splices the forward and aft skins to each other. A traditional representation of the assembly using a liaison diagram is shown in Figure 8-2(a). A Liaison diagram is an undirected graph where the nodes represent parts and the arcs represent liaisons (contacts or mates) between them [7]. A candidate DFC for the assembly is shown in Figure 8-2(b). As can be seen in the figure, it is a graph of mates only.

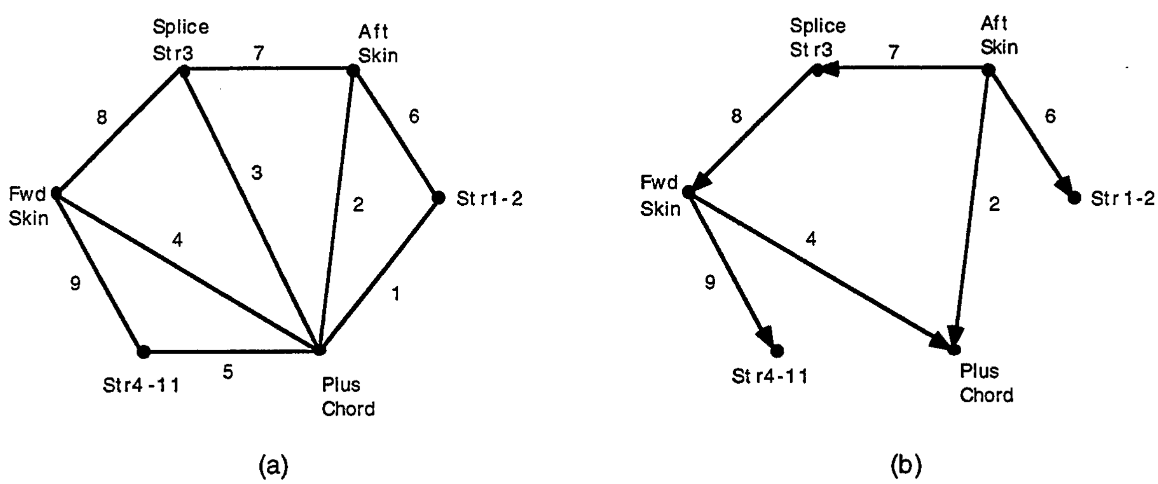


Figure 8-2: (a) Liaison diagram and (b) Datum flow chain for the assembly in Figure 8-1

The DFC in Figure 8-2(b) states that the location of Stringers 1-2 and splice stringer-3 is determined completely by mating features on the Aft skin. The splice stringer locates the Forward skin. The Aft and Forward skin together locate the Plus-chord. Mating features on the Forward skin locate stringers 4-11. Liaisons 7, 8, 2, 4, 6, and 9 are thus mates while liaisons 1, 3, and 5 are contacts. The features used to assemble the stringers to the plus chord

(liaisons 1, 3, and 5) should allow for absorption of part variations and avoid forming an over constrained assembly. This DFC and feature set were chosen to deliver a particular set of KCs. These are described in Section 5 and a complete discussion of the process is in [13].

8.3. Types of assemblies

Most models of assemblies represent the assembly as complete, i.e. with all its parts in place and all mates and contacts fastened. Therefore these models are not capable of addressing issues that occur during the act of assembling. Assembly planning involves considering a series of successively more complete assemblies. Incomplete assemblies may have unconstrained degrees of freedom that will be constrained when the assembly is complete. Yet these uncontrolled degrees of freedom or variations may cause the next assembly step to fail or may result in a mishapen final assembly, and thus have to be considered during design. In order to manage these issues systematically, we distinguish two types of assemblies.

8.3.1. Type-1 assemblies

Type-1 comprises typical machined or molded parts that have their mating features fully defined by their respective fabrication processes prior to final assembly. The variation in the final assembly is determined completely by the variation contributed by each part, assuming that all the "rules" of assembly (correct bolt torque, cleanliness, etc.) are followed. Assembly merely "puts the parts together" by joining their pre-defined mating features. The mating features are almost always defined by the desired function of the assembly, and the assembly process by itself has little or no freedom in selecting mating features or affecting final assembly variation.

Defined in terms of the DFC, a type-1 assembly is one where every part has at least one *mate* with at least one other part in the assembly. Fixtures, if present, merely immobilize the base subassembly and present it to the part being assembled in the desired position and orientation.

8.3.2. Type-2 assemblies

The second type of assembly includes aircraft and automotive body parts that are usually given some or all of their assembly features or relative locations during the assembly process. Assembling these parts requires placing them in proximity and then drilling holes or bending regions of parts, as well as riveting or welding. Final assembly quality depends crucially on achieving desired final relative locations of the parts, something that is by no means assured because at least some of the parts lack definite mating features that tie them together unambiguously. A different datum flow logic, assembly sequence, etc. will result in quite different assembly configurations, errors and

quality. It is possible to build a perfect assembly out of imperfect parts and vice versa by choosing an appropriate or inappropriate datum flow chain logic.

In type-2 assemblies, some mating features can be chosen to selectively propagate variation along certain directions and absorb in other directions. This can be illustrated in Figure 8-3 by simple 1-D slip plane type features.[19]

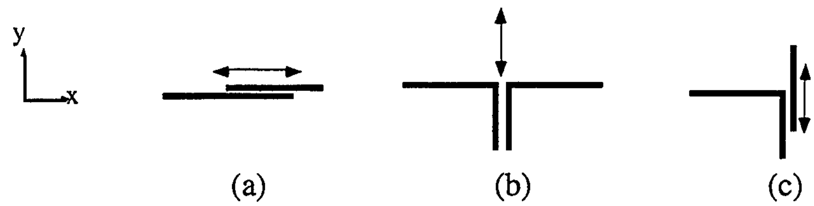


Figure 8-3: Some simple assembly features illustrating selective absorption of variation along the arrows

The slip plane in Figure 8-3(a) will absorb variation along x direction and transmit it along y direction while those in Figure 8-3(b) and (c) will absorb variation in y direction and transmit it along x direction. Hence, in type-2 assemblies, assembly design involves design of both location transfer and mating features.

Defined in terms of the DFC, a type-2 assembly is one where it is possible to have only ***contacts*** between all parts in the assembly. In such cases, the parts will have ***mates*** with fixtures used to locate them. Typically, a type-2 assembly will have a mixture of mates and contacts.

8.4. Assembly design and planning using DFC

Most assembly planning systems developed in the past have treated assembly planning as an activity separate from product design. Often a problem with this approach is that the choice of assembly method is not consistent with the design of the product because assembly considerations were not made during product design. This leads to fit-up problems during assembly that are hard to diagnose. The DFC allows for a top-down approach to designing assemblies. This approach starts with carefully identifying the assembly requirements from the top level customer requirements down to the fabrication of individual parts using a method called Key Characteristics (KCs). These resulting specifications then are used to define candidate datum flow chains (DFC) for the assembly.

Next, the mating and assembly features that carry the datums and establish the relationships imposed by the DFC are designed. Different procedures are employed for type-1 and type-2 assemblies. For the former, the

[19] Slip planes are well-known and widely used in the automobile industry.

selection of mating features is usually determined by considering function. For the latter, feature type and location selection are a crucial part of the assembly process design. The DFC is then used to classify assembly sequences based on the order of establishment of these dimensional references and identify assembly sequences that will deliver KCs consistently. The following sections describe this approach in detail.

8.4.1. Key Characteristics and DFC design

KCs come directly from the customer requirements and are flowed down in a systematic manner from assembly to subassembly to part level. [1] Identification of all the KCs and their flowdown for the assembly is a prerequisite to DFC design. Joints directly associated with the delivery of KCs should be designated as mates and tightly toleranced during the design and monitored during assembly process.

8.4.2. Mating feature design: designing locating schemes

In type-1 assemblies, the datum flow and mating features between parts are determined by considering almost exclusively the desired function of the assembly. Hence the designer may not have enough freedom to design the mating features specifically to suit assembly needs. However, in the case of type-2 assemblies, the designer has a lot more freedom to design these assembly mating features to locate parts with respect to each other or a fixture. In these assemblies, the choice of assembly features and DFC design are tightly coupled. Designing a locating scheme for these assemblies involves first determining at a very high level what part(s) locates what other part(s) in the assembly and then iteratively designing the assembly features that will accomplish the location. Since each arc in a DFC is a mate, an appropriate feature has to be chosen to accomplish the mate. This feature must constrain the required dof to perform its function as a mate and absorb uncertainties in other directions such as thermal expansion, etc. The absorption directions are perpendicular to the DFC mate directions. This is illustrated by the following example:

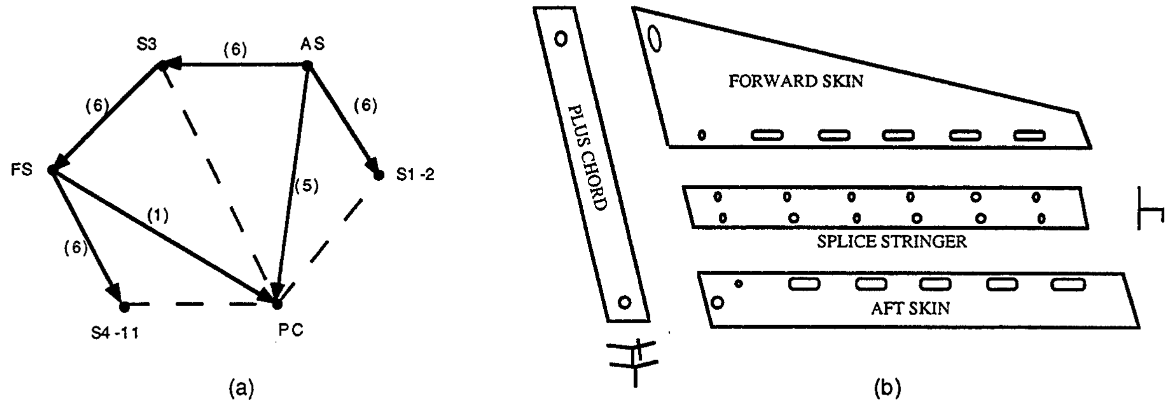


Figure 8-4. (a) A DFC for the assembly in Figure 8-1(b) a possible feature set implementation to carry the datum logic defined by the DFC in (a). Dashed lines are contacts.

Figure 8-4 (b) shows one possible mating feature set implementation of the DFC in Figure 8-4 (a). The numbers on the arcs in the DFC indicate the number of dof determined by the mate. Mates are solid lines in the DFC while contacts are dashed lines. These features are formed during fabrication and control the location of functional but non-mating features such as edges. The location of these edges in turn is driven by various KCs as described in the next subsection. The holes provide full planar location. The slots provide planar location perpendicular to their long axes and accommodate variation caused by thermal expansion and shot peen growth along these axes. The mating features are joined with temporary rivets until permanent ones are installed. All slots are drilled out to become full size holes for permanent fastening.

The DFC provides guidance on how to dimension and tolerance individual parts based on their presence in the DFC. The portion of the DFC that passes through different mating features within a part determines the critical chain within the part that needs to controlled tightly during design and fabrication. The tolerancing of this chain internal to the part will determine the error contributed by the part to the final assembly KC error distribution.

8.4.3. Decomposition and Subassembly design

The choice of which liaisons are to be mates and which ones are to be contacts determines the decomposition of the assembly and the permissible set of subassemblies. This choice is usually driven by the KCs for the assembly but can sometimes also be driven by assembly limitations.

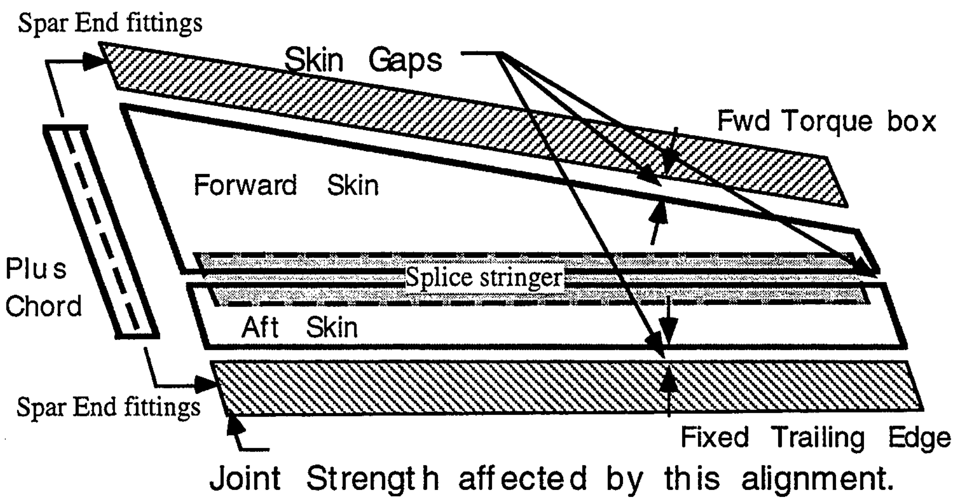


Figure 8-5: KCs for the assembly shown in Figure 7-8

This situation is illustrated here using the horizontal stabilizer shown in Figure 7-8 and Figure 8-5. It has three KCs:

- Inboard joint strength requires the Plus Chord, Forward Torque Box, and Fixed Trailing Edge be accurately aligned (nominal ± 0.005in), which flows down to:
  KC #1:plus chord alignment to spar end fittings.
- The skin gaps must be accurate and consistent (nominal ± 0.030in), which flows down to:
  KC #2: gaps between the skins on the upper skin assembly and those on the Forward Torque Box and Fixed Trailing Edge, and
  KC #3: gap between the forward and aft skins of the upper skin assembly.

(One of these was called PKC #2 in Section 7 to illustrate the chain metrics method.)

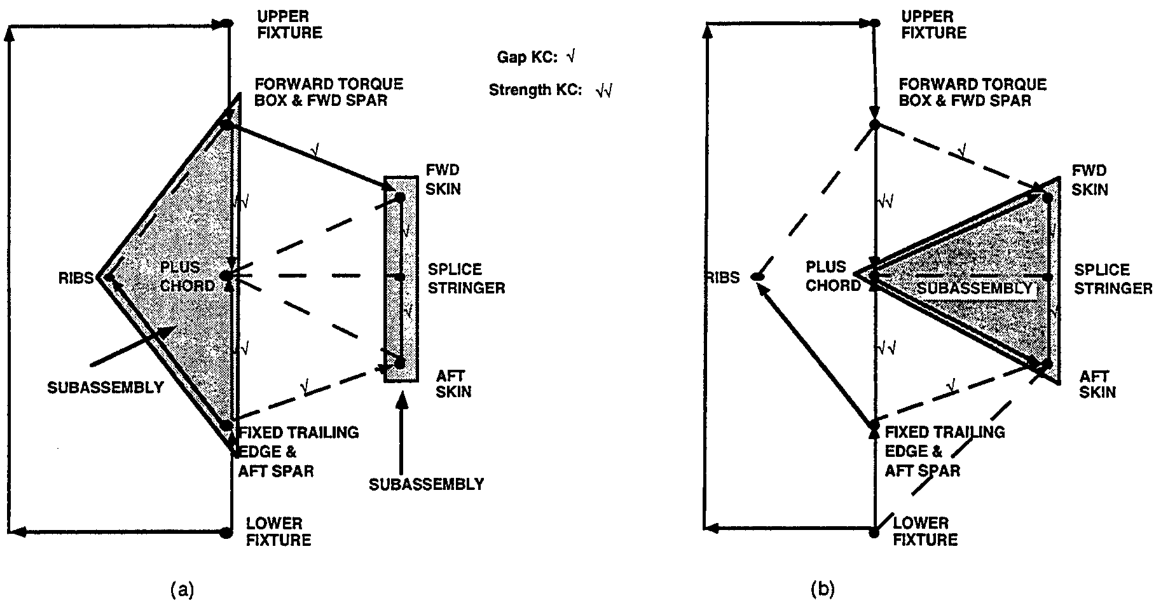


Figure 8-6: (a) Desired DFC for delivering the KCs for the assembly. This corresponds to decompositoin #2 in Figure 5-15. (b) DFC that was actually implemented due to assembly constraints. This corresponds to the current decomposition shorn in Figure 5-13. Grey areas are subassemblies.

A desired DFC to repeatedly deliver these KCs independently is shown in Figure 8-6(a). The plus-chord -skin and plus-chord-stringer joints are labeled as contacts as they are not directly associated with the delivery of any KCs. The assembly sequence resulting from this DFC was physically not realizable due to blocked access for installing fasteners. Hence a modified DFC shown in Figure 8-6(b) had to be designed to successfully assemble the parts. To achieve the KCs, the joints between the plus-chord and the skins are now defined as mates and controlled carefully during design and assembly. This resulted in a different decomposition of the assembly. Plus-chord is now part of the upper-skin subassembly. KCs 1 and 2 are no longer independent in this decomposition but are tightly coupled so that delivery of both cannot be guaranteed. The new DFC assigns a higher priority to the strength KC. The quality of the skin-gap KC is determined by the mates between the plus chord and end fittings and the mates between the plus chord and the skins. This KC is indirectly delivered.

8.4.4. Assembly sequence planning

Typically, an assembly can have a large number of feasible assembly sequences, based on geometric interferences. [De Fazio and Whitney [7], Homem De Mello [14], Bourjault [15], Baldwin et al [16]], It is not clear which feasible sequences will deliver all the KCs repeatedly. We describe an approach to assist pruning the assembly sequence graph into a smaller manageable set of assembly sequences using the DFC.

8.4.4.1. Assembly precedence constraints

Methods employed to generate all possible assembly sequences treat all liaisons as the same type and have not made the distinction between "mates" and "contacts." We argue that not all possible subassemblies are desirable and emphasize the need to only consider the assembly sequences that deliver satisfactory dimensional tolerance on KCs.

The design of a DFC involves the conscious decision of designing mates and contacts. As mentioned earlier, contacts do not define any dimensional relationships between parts and have to be established only after the mates that define the dimensional relationships are made. Using this argument, the following rule is imposed by the DFC:

Contact rule: *Only connected subgraphs in a DFC can form permissible subassemblies*

Subassemblies with only "contacts" between any two parts are not permitted because contacts do not contribute to a KC. This rule will thus generate additional assembly precedence constraints that eliminate subassemblies whose parts do not establish part of a DFC.

If the location of a part is defined by more than one part in the assembly, all the defining elements should be present in the subassembly before the part can be assembled. This argument is captured in the following rule:

Constraint rule: *Subassemblies with incompletely located (under-constrained) parts are not permitted*

The constraint rule imposes the condition that the in-degree of all but one of the nodes in a subassembly must add up to six. The one exceptional node could represent either a base part or a fixture, and has an in-degree equal to zero. This rule ensures that every subassembly has fully located parts.

Both these rules are equivalent to precedence constraints that take the following form, similar to [7]:

$$(i \,\&\, j) >= (k \,\&\, l)\,;$$

The operator ">=" means "must precede or concur with". The above constraint is read as: liaison i and j must be completed before or concurrently with, completion of (both) liaisons k and l (but not necessarily before or concurrently with either liaison k or l).

There are thus two sets of assembly precedence constraints: Geometric precedence constraints, and precedence constraints generated by the DFC. For a given assembly, each candidate DFC design will generate a different set of precedence constraints. But the geometric precedence constraints remain the same for a given assembly unless there are major changes in mating features

between parts. For the DFC shown in Figure 8-2, the precedence constraints imposed by the *Contact* and *Constraint* rules are shown in Figure 8-7. Note that the first three precedence constraints come from the *Contact* rule and the last two from the *Constraint* rule. $2 \geq 4$ and $4 \geq 2$ together signify that 2 and 4 have to be completed simultaneously. Subassemblies involving only plus-chord and stringers are not permitted by the Contact rule, as there are no designed mating features between these parts. The Constraint rule prevents subassemblies such as (Fwd-skin, Plus-chord, Aft-skin) subassembly since it has incompletely constrained parts.

8.4.4.2. Family of assembly sequences

Each DFC generates a "DFC-family" of assembly sequences. Sequences in a family share some common properties since they satisfy the same locating scheme defined by the DFC. This greatly reduces the number of sequences that must be investigated, as indicated in Figure 8-7.

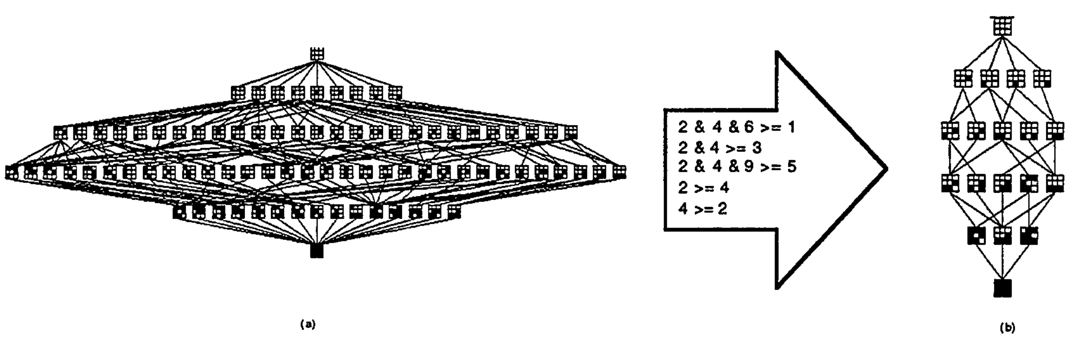


Figure 8-7: (a) Complete set of assembly sequences (b) resulting family of sequences after applying constraints imposed by the DFC

The assembly shown in Figure 8-1 has 312 feasible assembly sequences, as shown in the assembly sequence graph in Figure 8-7(a). Every box in the graph represents a feasible assembly state and every path from the top to bottom of the graph represents a feasible assembly sequence [17]. At every level, one part is added or one process is performed on the assembly. After applying the constraints imposed by the DFC, the family consists of only 28 assembly sequences shown in Figure 8-7(b).

8.4.5. Modeling fixtures in assembly operations

Fixtures are an integral part of any assembly process. In a type-1 assembly process, they immobilize the base subassembly and present it to the part being assembled in the desired orientation. On the other hand, in type-2 assemblies fixtures define the location of one part with respect to another during assembly. Most assembly planning approaches in the past have modeled the

assembly process strictly as adding parts and have not included fixtures in the modeling process.

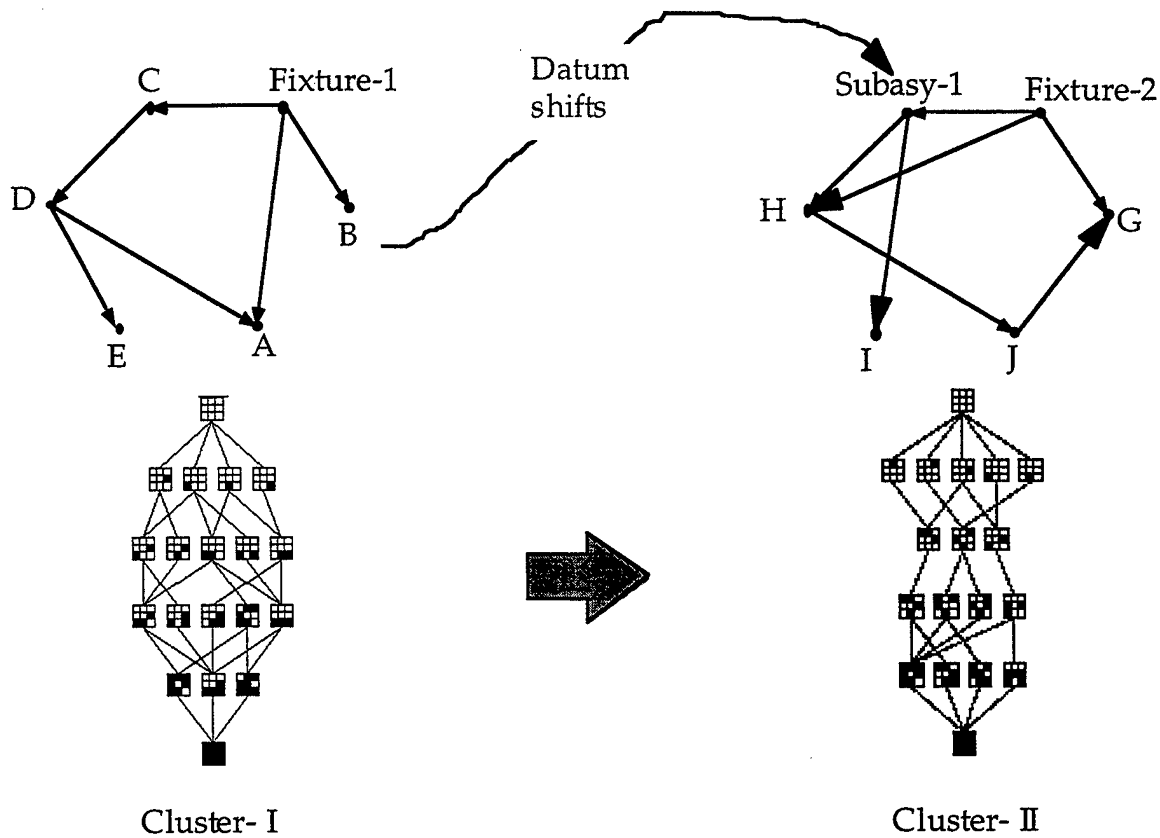


Figure 8-8: Modeling multiple assembly station assembly processes using DFC

We model assembly process for type-2 assemblies and type-1 assemblies involving fixtures as series of clusters of assembly operations. Each cluster has one fixture and one or more associated DFCs that control all the assembly operations performed at the fixture, as shown in Figure 8-8. By modeling this way, we avoid the problem of fixtures coming in and going away whenever there is re-fixturing. It allows us to represent the fixture as a part and it forms the node with zero in-degree (base node) that roots the DFC and starts the assembly process. Precedence constraints (both geometric and DFC imposed) and resulting assembly sequences are generated for each cluster. During a re-fixturing, we must be aware of datum shifts which occur if the subassembly is located differently on the next cluster. The entire assembly process is thus modeled using a piece-wise continuous chain formed by tracing the DFCs through one cluster along the datum shift line and into the next cluster. This chain determines how the KCs are delivered by the assembly process in multiple assembly stations and is an input to tolerance analysis.

8.5. Evaluating alternate DFCs

A DFC highly constrains both assembly design and process. The design of mating features at part interfaces, tolerances on individual features and subassembly configurations are limited by which joints are mates and which ones are contacts in the DFC. The locating scheme, tolerance chains for the KCs, family of permissible assembly sequences and quality of resulting KCs are also determined by the design of the DFC. Hence it is essential to develop analysis tools to evaluate and compare alternate DFCs. Some of the analysis can be qualitative, as there is no such thing as an optimal DFC or optimal assembly sequence. Different DFCs can be preferred under different operating conditions. Some of these analysis tools will be described below:

8.5.1. Decomposition and subassembly analysis

The decomposition of the assembly into subassemblies and the design of the DFC are related, as described in Section 6.3. The subassemblies deliver segments of KC chains and can be used as indicators to monitor the status of KCs during the assembly process. The percentage error contributed by individual subassemblies can be used for error budgeting and tolerance allocation purposes. Some subassemblies are more desirable than others in making these observations. For example, subassemblies where the status of the KCs is not predictable until the last few assembly operations can be undesirable for this reason. Since different DFCs will result in different permissible sets of subassemblies, relative desirability of subassemblies can be used as a metric to evaluate alternate DFCs.

8.5.2. Variation propagation analysis

An important metric used to choose between alternate designs and assembly sequences is the variation associated with the final assembly KCs accumulated from individual part and fixture variations, assembly errors, etc. The goodness of a locating scheme imposed by a DFC is evaluated by performing variation propagation analysis on families of assembly sequences, instead of individual assembly sequences. In type-1 assemblies, accumulated variation causes assemblability problems due to interference, at an intermediate assembly operation [18]. In type-2 assemblies, it is possible to make in-process adjustments during assembly and hence re-define the distribution of variation [19].

The tolerance chains for any KC can be readily derived by traversing the DFC between the nodes (parts) of interest. The DFC is an acyclic graph and all the paths between any two nodes collectively define the tolerance chain between the two nodes. Hence, there is a unique tolerance chain in the DFC for every KC. A graph similar to the DFC can be constructed at a part level to

determine how to define all the datums within each node (part) that this tolerance chain will pass through so that the KC will be achieved.

8.5.2.1. KC deliverability analysis

In type-2 assemblies, there is freedom to consciously select at least some of the features that define ***mates*** and ***contacts***. The contact features can be designed to selectively absorb variation along certain directions and propagate certain others (for example, slip planes, peg-slot joints, designed gaps, etc.)[19]. The ability to make in-process adjustments in type-2 assemblies is due to the presence of ***mates*** that are completed by fixtures and ***contacts*** that allow for variation absorption in the assembly. The amount of variation tuned out and the directions along which the variation can be tuned out is determined by the type of the contact feature. Variations accumulated in ***mates*** between two parts cannot be tuned out directly. However it may be possible to tune out their effects on final assembly dimensions when some ***contacts*** are established in downstream assembly operations.

Variation propagation algorithms that can determine resulting variation distribution of KCs in the presence of in-process adjustments have been developed to evaluate different assembly sequences [19, 20]. Different assembly sequences will establish contacts at different stages of the assembly process and hence will have different resulting variation distributions. Thus for type-2 assemblies, the state of the tolerance chains at any assembly station is a function of the path taken to arrive at that station. We call this property of type-2 assemblies as ***path dependency.***

8.6. Conclusions and Future Work

This Section presents a top-down design approach to link logical design of assembly layouts with KC flowdown, assembly sequence, and tolerance analyses, and create assembly sketchers and analyzers capable of analyzing assembly processes before detailed geometry has been designed. The DFC permits layout designers to think through possible hierarchies of dimensional datums and then to design chains of these datums to control how parts are located with respect to each other. It is useful for selecting dimensional datum strategies and assembly processes that are best able to meet final assembly requirements. The DFC emphasizes the need to distinguish the joints that define dimensional constraint from the ones that are redundant location wise and merely provide support once the parts are located.

The Section describes the role of the DFC in subassembly design, assembly modeling and planning. Algorithms to translate the hierarchy imposed by a DFC into assembly precedence constraints were developed and presented in this paper. These algorithms are used to generate families of

assembly sequences that share the same locating scheme. This reduces the design space to a small set of workable assembly sequences that are consistent with part design. In type-1 assemblies, since there are no in-process adjustments permitted during assembly, all sequences in a family have the same probability of delivering the key characteristics. However, in type-2 assemblies these sequences have different probabilities of success due to the ability to make in process adjustments during assembly. The DFC provides for a common environment to address a broad range of assembly planning issues for both types of assemblies.

9. Corrective Action Cases[20]

Corrective action (CA) is a response to problems encountered by manufacturing firms during fabrication and assembly of the product, such as assembly of mechanical structures like automobiles and aircraft. CA occurs between the time when design reaches completion and initial production and delivery begins. This is a time-critical point in product development, so CA must be conducted efficiently and effectively to eliminate the problem's root cause that can potentially compromise product performance and quality, minimize the schedule delay in the production schedule, and minimize the lasting impact on production cycle time and hence unit cost.

CA was chosen for study during this program as a means to identify upstream design practices in product development that have significant impact on a firm's ability to deliver a product on-time, to cost, and meeting performance specifications. Assemblies were specifically chosen for study because they represent the integration of all the contributors to product performance:

- individual part design, fabrication process, and function

- assembly design, assembly process, and function

- organizational issues, including the role of each part or assembly supplier in the design and realization of the product.

When investigating assembly problems, the participants in CA must identify a root cause from among three potential groups of causes: an incorrectly fabricated part, an assembly process or tool problem, or a design error. In automotive and aircraft assembly, the structures and processes are sufficiently complex to make the identification of these potential causes difficult, and the identification of the root cause a distinct challenge that requires a systematic approach involving people from several disciplines and organizations. In both industries the recent trend has been to buy parts from vendors, so the organizational complexity continues to grow as groups from geographically dispersed organizations are involved in the process.

This section of the report summarizes approaches to CA of assembly problems from the automotive and aerospace industries to demonstrate how an integrated approach to product development can have significant impact on the ability to quickly solve assembly problems. The details are in [Cunningham 1996]. A proactive approach observed in the automotive industry prepares for corrective action during product development by

[20] This sectin is adapted from [Cunningham 1996]

creating an integrated set of information and diagnostic tools that help isolate possible root causes quickly when assembly problems occur. This study also demonstrates the use of a visual tool - called the Contact Chain - for communicating potential root causes in an illustrative format that can be used to communicate across disciplines and organizations. The systematic method to isolate root causes and the Contact Chain serve as the basis for suggestions to improve approaches to CA in both industries.

The CA methods were demonstrated in terms of two case studies: the front end of the 1995 Ford Explorer and the inlet to the McDonnell-Douglas C-17 engine housing.

9.1. Case Studies

This section introduces two case studies used to illustrate the CA concepts in this report. The Ford 1995 Explorer Front End is the automotive case study, while two assemblies from large aircraft are the case studies from Vought. Both the business environment for each company and the assemblies are described in detail.

Automotive and aerospace assembly at first glance appear quite different. The most striking differences are in production rate and amount of hands on, or "touch labor" (as opposed to automation) involved in the assembly of the products. Ford completes production of an Explorer every 47 seconds at Louisville, and every 70 seconds at St. Louis. Vought completes production of one C-17 Nacelle and one 767 Horizontal Stabilizer every 10-14 days. Ford's body assembly lines are nearly completely automated, with the use of re-programmable robots along the line in St. Louis to allow for better flexibility over the life of the equipment and more economical but less flexible equipment on the assembly line at Louisville. Vought assembles the Nacelle and Horizontal Stabilizer almost entirely by hand, except for automated installation of large numbers of fasteners.

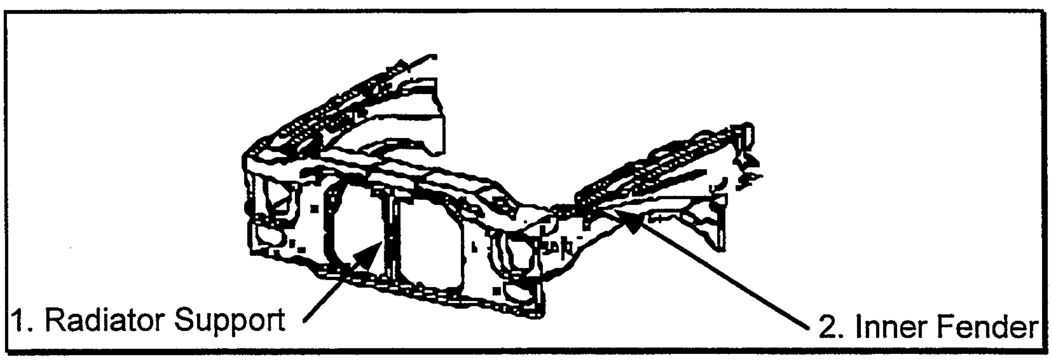
Despite the differences in size, production rate, and amount of automation, closer inspection of the problem changes this view and reveals just how similar automotive bodies and aircraft assemblies are. Both are in the main made of sheet metal/composite parts and require large, expensive, inflexible fixtures to position the parts for assembly. Both types of assemblies have extremely tight tolerances, with almost identical values for the gap tolerances between parts in the assemblies. Both are dependent on fastening methods to combine the parts, with a car body having thousands of welds and a Nacelle Inlet or Horizontal Skin Assembly having thousands of rivets. Both are designed and procured in a complex web environment. Both are increasingly exploiting Computer Aided Design (CAD) and Manufacturing (CAM) tools in the design process.

9.2. Ford Ford and the 1995 Explorer Front End

Since the mid-1980s, the U.S. auto producers have focused on improving quality and cost in response to the major market penetration made by the Japanese auto manufacturers [Womack, et.al.]. Ford has incrementally improved its "dimensional control"[21] process over the last five years since its beginnings in the Body and Assembly Operations group. Over that time, the small-truck group at Ford has steadily implemented improved dimensional control practices, including the coordination of Measuring Points and Master Locators as described in Section 7-5 and the increased use of three-dimensional tolerance analysis [Assembly 9/8/95]. The small-truck line introduces one new vehicle approximately each year, which has permitted Ford to incrementally implement changes, product by product, as opposed to implementing sweeping changes to their process.

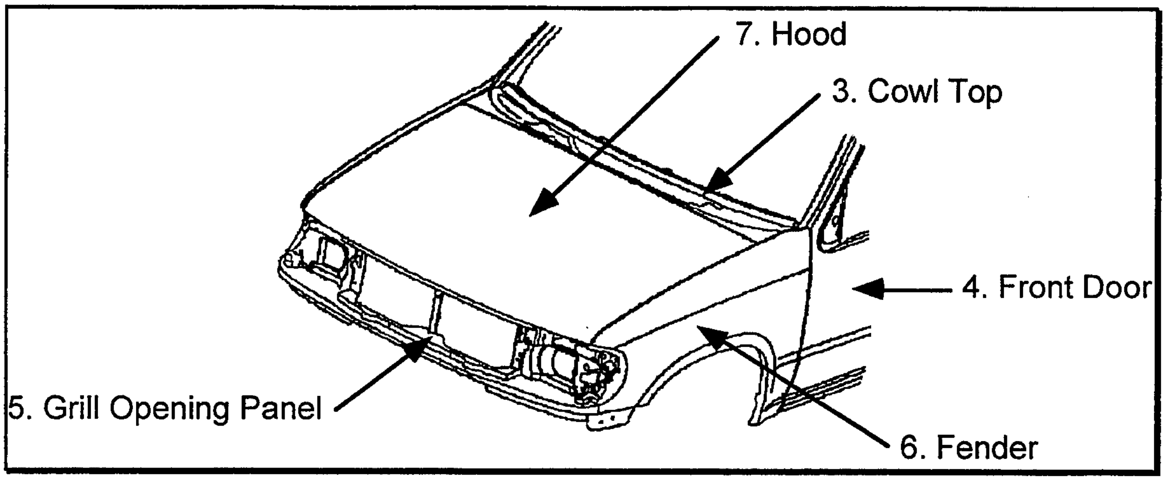
9.2.1. Explorer Front End Assembly Description.

The 1995 Explorer Front End was restyled reconfigured to house several modified components in the engine compartment. Figure 9-1 shows the parts that make up the Front End of the Explorer, with Figure 9-1a showing the parts making up the frame, and Figure 9-1b showing the closure panels, or parts on the outside of the vehicle.



a.

[21] Dimensional control is a program to understand and control variation of important dimensions on the vehicle.



b.

Figure 9-1. Explorer front end parts (a) frame and (b) closure panels, numbered according to the assembly sequence. These are structural parts whose functions are to house the engine and drivetrain components and support esthetically pleasing fenders. The Explorer is a body-on-chassis vehicle so these parts do not play a significant role in crash energy absorption. The parts are all stamped galvanized steel made by stamping and forming processes, except for the Grill Opening Panel which is compression molded plastic. The framing parts are placed in position by automated assembly fixtures and are fastened by automated welding machines. The Hood, Fenders, and Doors are placed by manually operated fixtures and attached with threaded fasteners.

9.2.2. Web of the Explorer Front End.

Figure 9-2 shows an exploded view of the Explorer Front End labeled with the name of each part, tooling, and check fixture supplier. The assembly plant makes no parts for the vehicle, and only one part is made by a Ford stamping plant; 8 suppliers provide parts for Front End. Three different tooling vendors provided the Fender Assembly Tooling, Frame Assembly Line, and "Hayracks." The check fixtures represented include the Fender Check Fixture and the Blue Buck. A total of 14 organizations are represented in this diagram.

The Budd Company is a major supplier to Ford for the Explorer, providing all sheet metal components that are visible on the outside of the vehicle, except the Hood. These parts are critical because they are responsible for delivering the vehicle appearance. The Budd plant in Shelbyville, KY, approximately 30 miles from the Louisville Assembly Plant, produces most of these parts. The students who spent the summer 1994 research period at these plants found the relationship of these two companies to be a prime example of the well coordinated organization demonstrated in our studies of CA at Ford.

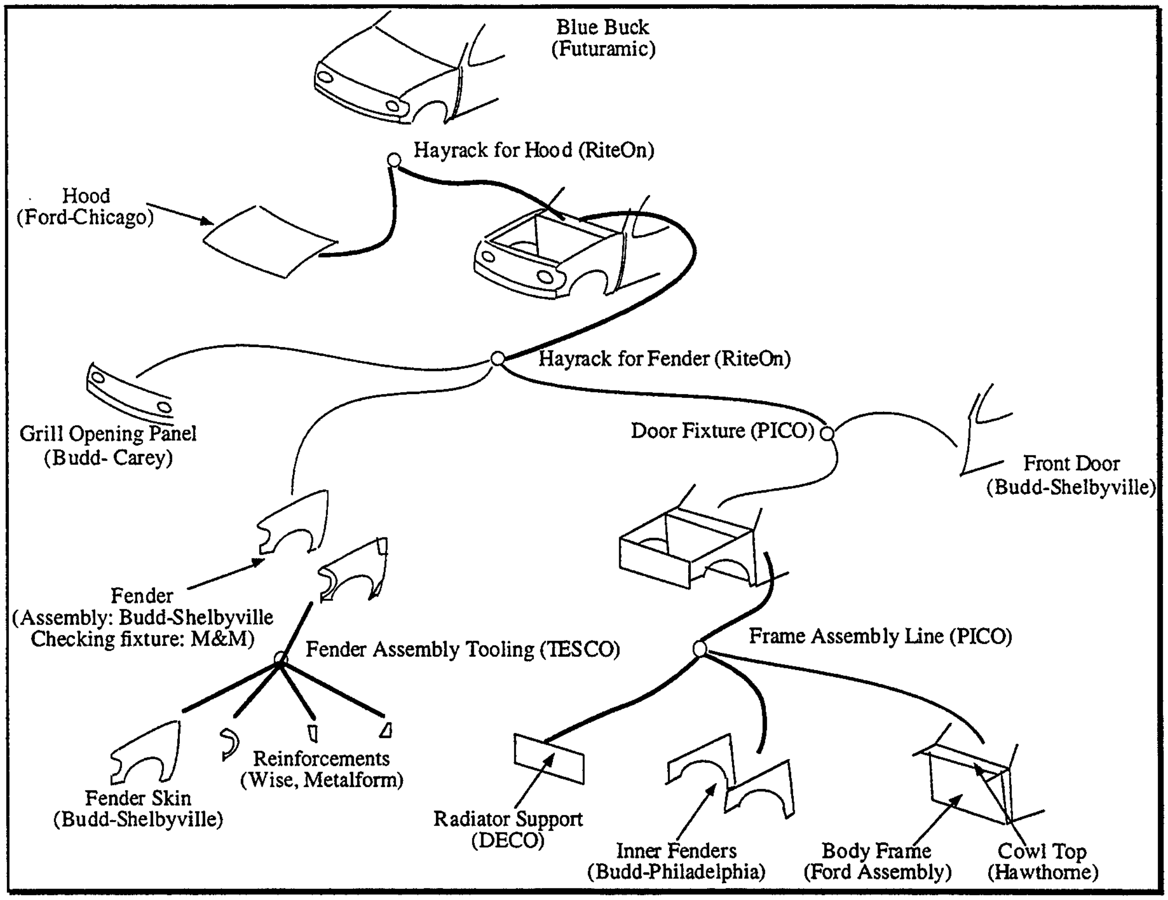


Figure 9-2. Explorer web (following a figure created by Soman and Chang [Fine]).

9.2.3. Ford Explorer Body KCs: Steps and Gaps.

The Key Characteristics for the assembly, which are strictly aesthetic to satisfy the appearance requirements, are the steps and gaps[22] along the outer body panel interfaces, defined in Figure 9-3. Steps and gaps are shown schematically in Figure 9-4. There are other functional attributes, however, such as the quality of sealing for noise and environmental protection of the cab, and the ease with which the hood and doors can be

[22] The terms "flushness" and "margins" are often used in automotive body assembly jargon.

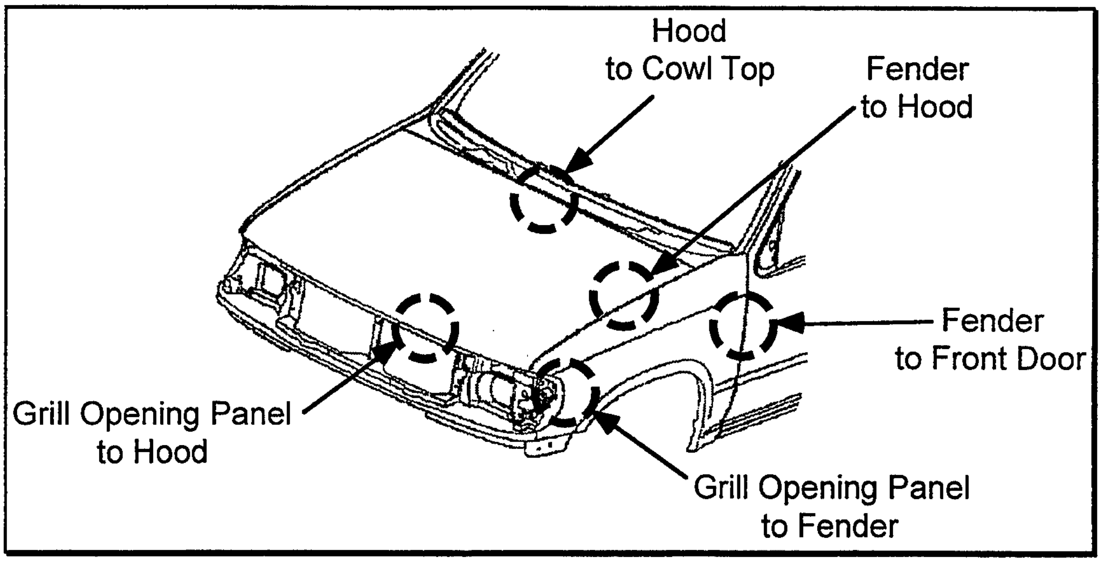


Figure 9-3. Location of KCs on the Ford Explorer Front End.

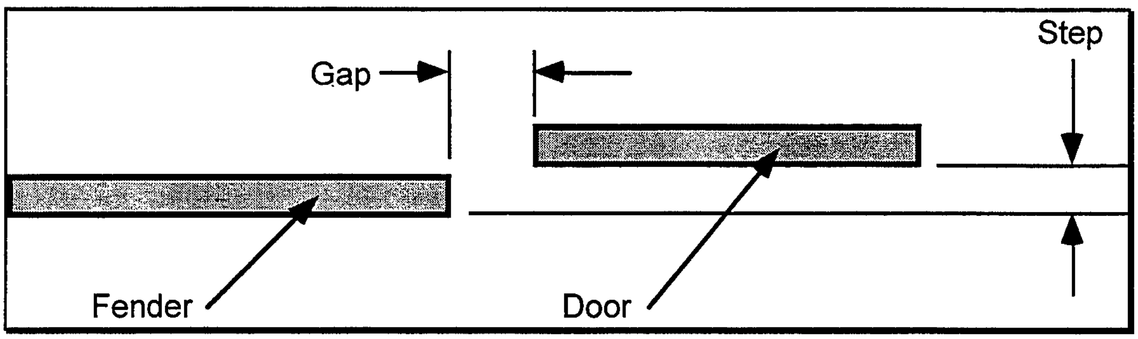


Figure 9-4. Definition of Steps and Gaps

closed by the passengers, that are related to consistent margins along the body panel interfaces. Tolerances on these gaps are typically on the order of +/- .030 to .060in.

The issues on which our research team focused on were assembly issues pertaining to the alignment of these parts, with two examples cited here and [Chang].

9.3. Vought C-17 Nacelle

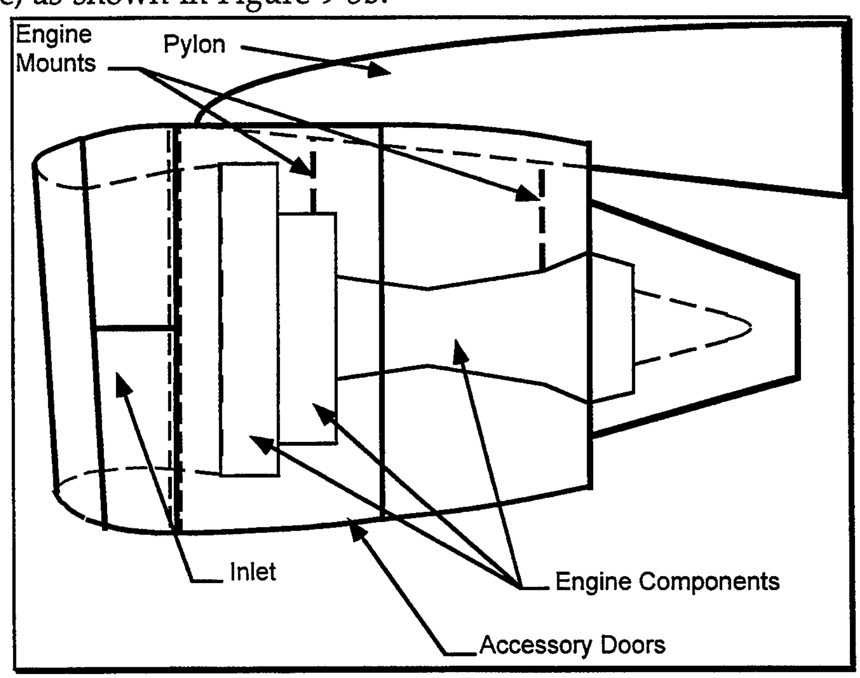
The C-17 is a large military transport aircraft used to move large payloads of equipment and people to all parts of the globe. The C-17 is unique among other large aircraft in its ability to operate at extremely small airfields; the aircraft can land on a runway less than half the length of those at most major airports and can turn around in a small circle. These capabilities provide the

Air Force with the ability to deliver much larger quantities of material to more remote locations than has been possible in the past.

9.3.1. The C-17 Nacelle Inlet Assembly Description.

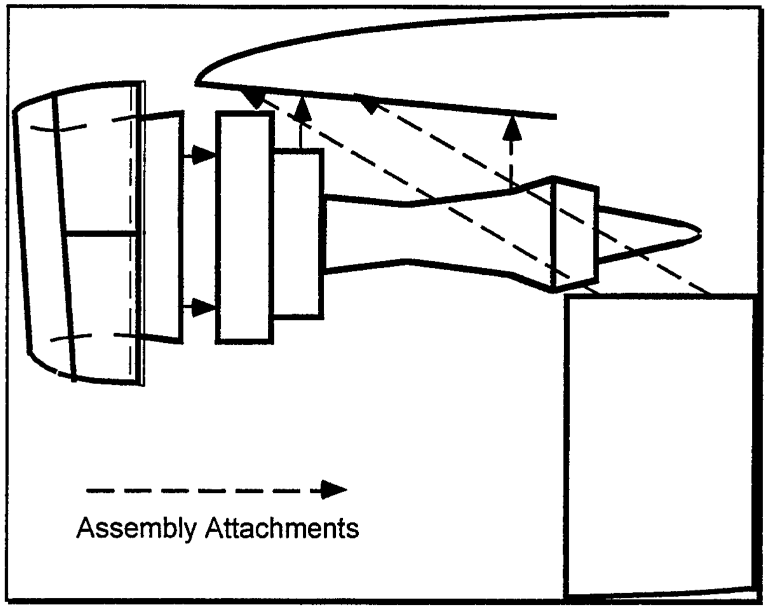
There are four Nacelles on the C-17[23], which include a few unique aspects that set it apart from other Nacelles similar in size. These unique capabilities are mainly located at the aft end of the Nacelle, directing airflow in several directions to assist in landing on short runways, turning the aircraft around, etc. The case study in this thesis is the Inlet assembly of the Nacelle, which is mainly common technologically to commercial aircraft nacelles with the exception of the use of composite materials for weight reduction on several parts; the use of composites will be eliminated upon introduction of the redesigned Nacelle on the next aircraft purchase, so the C-17 Nacelle Inlet is representative of common military and commercial technology.

Figure 9-5a shows the major assemblies at the front of the C-17 Nacelle. The Engine and Accessory Doors attach to the Pylon, and the Inlet attaches to the Engine, as shown in Figure 9-5b.



a. Major assemblies of the Nacelle.

[23] Vought builds a Nacelle once approximately every two weeks.



b. Interfaces of the major assemblies.

Figure 9-5. Major assemblies on the nacelle.

9.3.2. Web for the C-17 Nacelle Inlet.

Figure 9-6 shows the web for the Nacelle and its attachment to the C-17. Below Vought are the suppliers for the parts shown in Figure 9-5. Vought's components integrate with the Pylon, built by the MDA plant in St. Louis, and the Engine built by Pratt and Whitney. Assembly of the Pylon to the wing, and then the Nacelle components to the Pylon, occurs at the MDA C-17 assembly plant in California. As shown in an example in Section 7, this web complicates the ability for Vought to manage the KCs described below.

9.3.3. KCs: Steps and Gaps.

The C-17 is a transport aircraft used for world-wide operations, so its range is a significant requirement by the Air Force. Like the Explorer, the high-level KCs on the Nacelle that Vought and MDA have identified are steps and gaps at the "joints" (i.e. interfaces, like on the closure panels of the Explorer) along its interior and exterior surfaces, shown in Figure 9-7. These KCs are strictly functional because the increased drag induced by steps and gaps was causing the aircraft to fail testing of its operational range early in the program. The Nacelle was suspected to be a major source in adding to the drag on the airplane, with steps and gaps designated the probable cause.

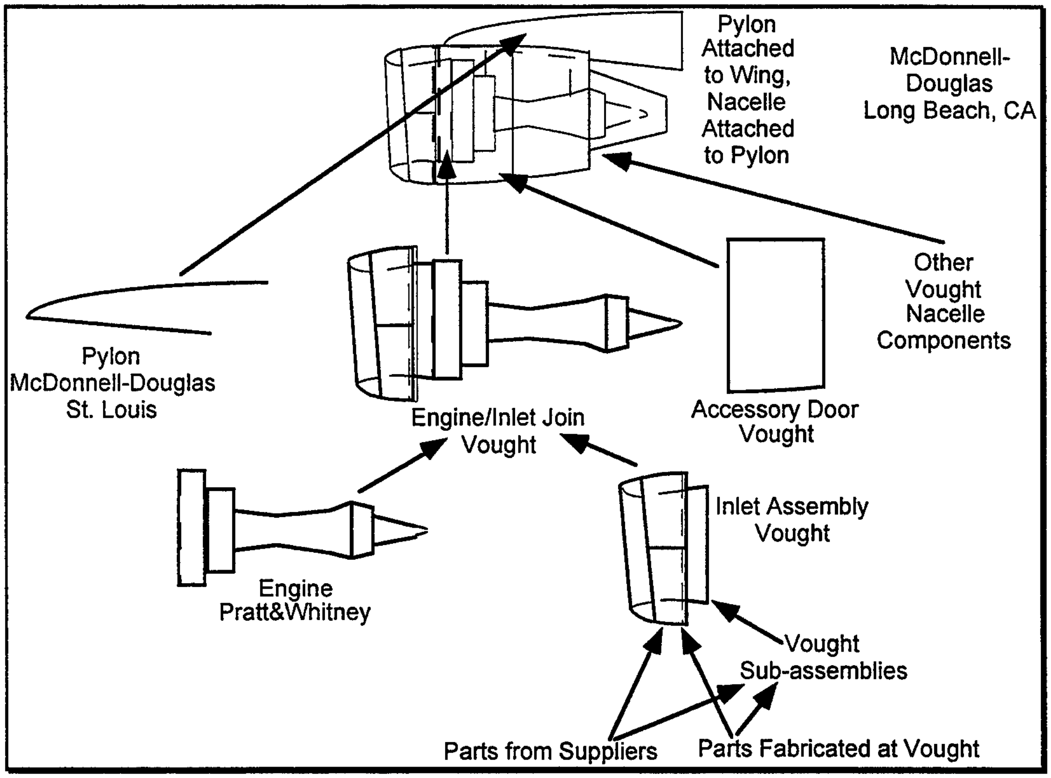


Figure 9-6. C-17 Nacelle web.

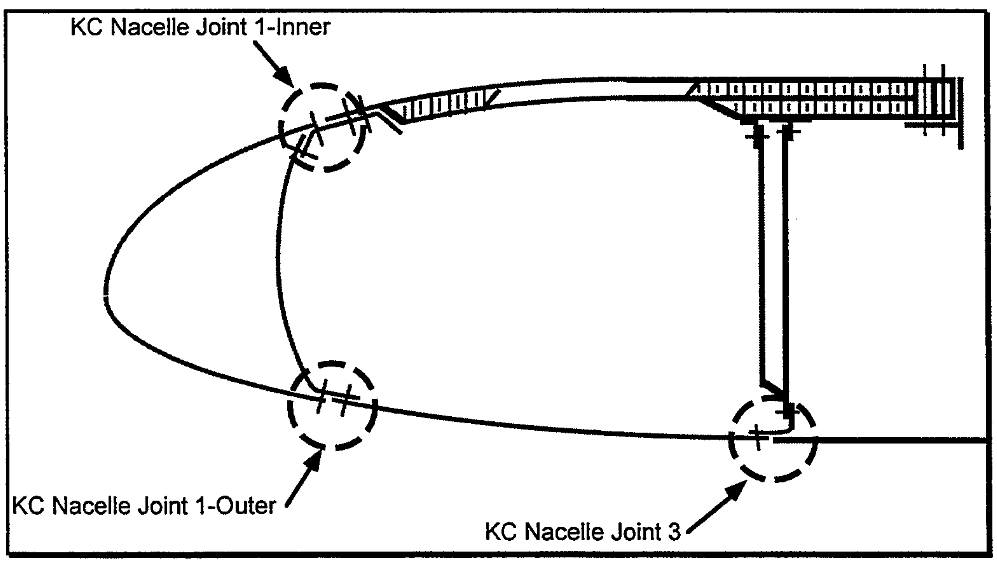


Figure 9-7. Joints on the Inlet.

Throughout the program, Vought has had difficulty meeting the step and gap tolerances, which are in a range of 0.012 to 0.090in, so most Nacelles have required waivers for acceptance. A great deal of re-work on assemblies has been required to improve the steps and gaps. Because final assembly of the Nacelle onto the Pylon occurs on the airplane, many step and gap non-

conformances are not found until that stage, when MDA is close to its required delivery date to the USAF. Joint 3 is especially important because Accessory Doors and the Inlet are interchangeable parts on the C-17, so any inlet must fit to any engine and any Accessory Door must fit to any Pylon. Because these parts are interchangeable, custom fitting the steps and gaps at Joint 3 is prohibited so the assembly process cannot rely on work-arounds specifically tailored to custom fit each set of parts.

9.3.4. The contact chain as a web mapping tool

The Contact Chain helps to document and communicate the role of each member of the web on the realizations of system-level features of the product. An example of the Contact Chain is the web map that affects the gap at Joint 3 of the C-17 Nacelle. Figure 9-8 shows the parts that interface at this joint. At first glance, it appears the gap between the Cowl Skin and Accessory Door is established directly at the interface.

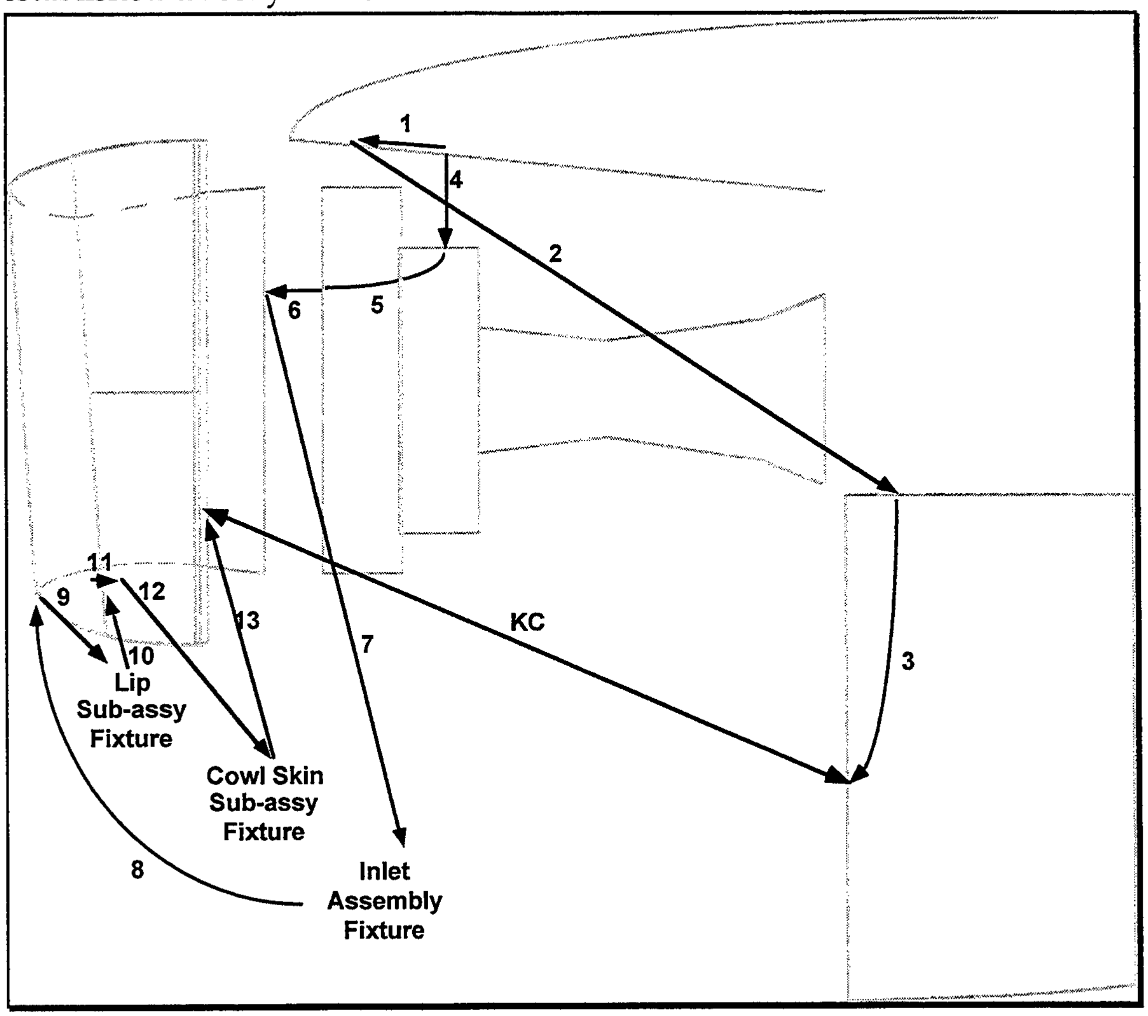


Figure 9-8. Contact Chain for C-17 Nacelle Joint 3 gap.

However, when the true contributors to this gap are documented more carefully, the impact of the web on the ability for Vought to control this gap is revealed. Figure 9-8 shows that the Contact Chain links include:

1. the dimension on the Pylon between the points that attach the Accessory Door and the points that attach the Engine
2. the interface of the Accessory Door and Pylon
3. the dimension of the Accessory Door from its attachment points to the Pylon to the edge that interfaces with the Cowl Skin
4. the interface of the Pylon and Engine
5. the dimensions of the Engine from the interface with the Pylon to the interface with the Engine Ring
6. the interface of the Engine and Engine Ring
7. the interface of the Engine Ring and Inlet Fixture
8. the dimension of the Inlet Fixture between the Engine Ring locators and Lip locators
9. the interface of the Lip and the Inlet Fixture
10. the dimension of the Lip from front to back, which is set by the Sub-assembly used to trim the Lip and set its dimension
11. the interface tool used to space the Lip and Cowl Skin
12. the interface of the Cowl Skin to its Sub-assembly Fixture, which locates Cowl Skin at the end opposite the end that it interfaces with the Cowl Skin
13. the dimension on the Cowl Skin between its forward edge and aft edge which is trimmed in the Sub-assembly Fixture.

What appears to be a simple problem, a gap between two parts, is not so simple when the actual influences on that gap are understood. By documenting the Contact Chain, the organizations that have an effect on the joint are understood and this can be used to communicate these influences between the organizations. The Contact Chain also points out parts and tools that have an effect on this gap. For example, the section of the Inlet Fixture that locates the Engine Ring is removable. This section is detached each time the Inlet is removed from the Fixture. Therefore, the variation with which this section of the Fixture is attached must be accounted for, which is represented by link #8 in the chain in Figure 9-8. By just considering parts, this effect would be ignored.

9.4. Ford Corrective Action Process

This section describes the systematic process Ford uses in corrective action (CA), how this process is driven by the upstream activities Ford conducts to prepare for CA, and the involvement of all members of the web in these upstream activities.[24] The CA process is described first to show how critical information and diagnostic tools are used to focus the investigation, which reveals the impact of the upstream activities on the ability to conduct a systematic investigation. Next, the information and diagnostic tools are

[24] These observations include my own at St. Louis and those of Minho Chang and Narendra Soman, Mechanical Engineering Ph.D. students on this project, at Louisville.

described in greater detail, along with the upstream activities that create the information and tools. The section concludes with a brief discussion of employee belief in the usefulness of this process and management's continued emphasis of its use.

9.4.1. The 8 Discipline (8D)

9.4.1.1. Steps in the 8D Process

When faced with assembly problems during production launch, Ford and its suppliers follow a methodical approach to problem solving called "The 8 Discipline" (8D). The steps in the 8D process are:

1. Establish the team - get a team together with the proper skills to fix the problem

2. Describe the problem - define the problem explicitly, not the symptom. The assembly problem is often a symptom of a larger problem, so this step may require iteration as more is learned while conducting subsequent steps.

3. Contain the symptom - perform a work-around to prevent the customer from being affected by the problem

4. Find and Verify the Root Cause - classify the problem following the process described below, identify the root cause, and make the problem come and go to prove the root cause has been isolated

5. Choose Corrective Action and Verify - verify with data showing the effectiveness of the CA

6. Implement Corrective Action and Validate - validate with data showing the CA is effective

7. Prevent System Problems - document the change to ensure similar issues do not arise

8. Congratulate the Team

The process emphasizes forming a group of investigators, from any organization necessary, and finding the *root cause* and confirming the right action was implemented.

9.4.1.2. Classification of the Problem

The 8 steps listed above tell the team what to do, but not how to do it. It is in the execution of this process where the efficiency is revealed. The key to Step 4 in the process, finding the root cause, is a method Ford uses to classify the problem into one of three categories early in the investigation [Prevent

Recurrence]. The three categories are general and are the same as those found in aircraft assembly CA:

- design - an error in the geometric definition of the product

- quality - incoming parts not meeting design intent

- tooling - a problem with fixtures, tooling or some aspect of the assembly process

By achieving classification, the investigators focus their efforts and resources toward finding the root cause from among the right group of potential causes and eliminate effort wasted on fruitless searches for the root cause among the wrong groups.

The flowchart depicted in Figure 9-9 shows the steps taken to classify an issue, documented through interviews and activities observed at the assembly plants by our team. This flowchart applies to conditions when the classification or solution isn't immediately obvious; e.g. if the cause is an obvious tool error, they will immediately try to solve that problem without considering quality or design. Though the flowchart is fairly simple in context, it contains two key steps where information is accessed and diagnostic tools are used to eliminate potential categories of problems.

9.4.1.2.1.Step 1: Obtain Part Data.

After a problem is defined and potential causes are identified, Step 1 in Figure 9-9 is to obtain measurement information for the part(s) in question. This is obtained by calling the vendor and requesting data at specific Measuring Point(s)[25] taken on the most recent production parts. (The origins of these data are discussed in Sections 4.4 and 9.7.) The Measuring Point(s) data requested will reveal the quality of the incoming parts, and whether a dimension on a part is out of specification and therefore the cause of the problem. Because the data requirements were developed in conjunction with the vendors, such requests are usually answered quickly, often within minutes.

[25] Measuring points are places where the product is measured, as described in Section 7.6.1.1

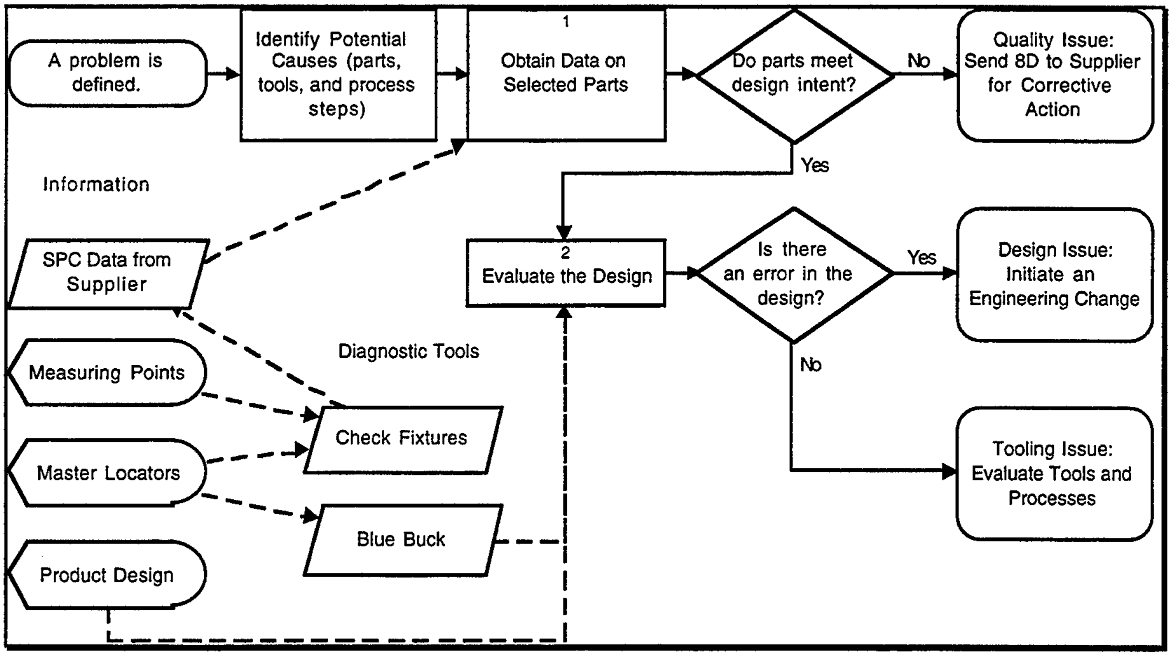


Figure 9-9. Process followed to classify a problem as quality, design, or tooling when attempting to find the root cause (8D step 4).

9.4.1.2.2.Step 2: Evaluate the Design.

There are two methods available for evaluating the design. First, the plant has on-line access to the digital definition of the parts on a common CAD system used throughout Ford. The system allows the user to view and evaluate the digital definition of the product, Measuring Points, and Master Locators[26]. Second, the lead plant for each vehicle, Louisville in the case of the Explorer, has a tool called the Blue Buck that provides the Master Locators for all parts so they can be physically assembled without the influence of the process and tooling. This allows for a physical build-up of the digital definition with the parts in the as-produced condition. The results of these two methods allow the investigators to determine if the problem is the product design itself, and if so, to initiate a design change. An evaluation of the digital definition can be made directly by the person leading the investigation.

If the problem is neither a quality or design problem, then by default the problem is classified as a tooling issue - a problem in the assembly process or tooling and the investigation focuses on these potential causes in the assembly plant.

[26] Master Locators are features on the parts used to locate them on assembly tools and check fixtures, as described in Section 7.6.1.2.

9.4.2. Information and Diagnostic Tools Accessed in the Process

The flowchart in Figure 9-9 identifies four types of information critical to the classification of an issue as a quality, design, or tooling issue. By tracing the dashed arrows backwards in Figure 9-9, it is clear that the two critical steps in the classification of a problem are supported by the common information and the diagnostic tools.

9.4.2.1. Information and Diagnostic Tools Accessed in Step 1 of Figure 9-9

The Ford assembly plant's ready access to SPC data can be traced back from Step 1 in Figure 9-9, via the dashed lines, to the upstream coordination of check fixtures, which are built based on the coordinated Measuring Points and Master Locators.

9.4.2.1.1. Measuring Points.

Measuring Points are locations on a part used by Ford and its suppliers to coordinate monitoring of all parts. The Measuring Point scheme allows the assembly plant to quickly reference a dimension to a vendor when discussing problems or requesting data. The Measuring Points are monitored at the correct locations on check fixtures at the supplier's facility. The intent of the Measuring Point coordination is to have data available for the CA team in advance. This data is often sufficient to determine whether the issue might be due to a quality problem, so only rarely are additional measurements on parts required to be performed at locations other than those designated as Measuring Points [Ford Interviews].

Ford uses two sets of Measuring Points. In initial production, hundreds of points are used on parts until the fabrication process is deemed capable of holding the tolerance and required C_{pk}. Once a process is deemed capable, a far lower number of points are measured on approximately five percent of the parts produced so process monitoring continues in an economic manner. If requested by the assembly plant, the supplier can easily change back to monitoring all points.

Measurements are taken on Key Characteristics.[27] For the case study discussed here, the KCs are the steps and gaps along the hood, grill, fender, and door interfaces, so there are many Measuring Points along those parts at these edges of the parts, and on the parts in the body frame that Fender to Hood interface. Figure 9-10 shows a representative set of Measuring Points on parts along a KC. While six Measuring Points are shown on each edge in Figure 9-10, there may be ten times that number along that same edge early in

[27] Ford uses the name "Significant Characteristics."

production until the fabrication process is capable of consistently delivering the required dimensions and C_{pk}.

9.4.2.1.2.Master Locators.

Master Locators are physical features at known locations used to position a part in the global coordinate system of the product. At Ford, the same points are generally used in all steps of the fabrication and assembly processes[28], and in all the diagnostic tools (i.e. the Blue Buck and check fixtures) used to monitor the process to provide consistency. Cases where Master Locators used in one assembly step that cannot be used in the subsequent step are determined during the upstream design process and agreed to by all parties involved in that decision.

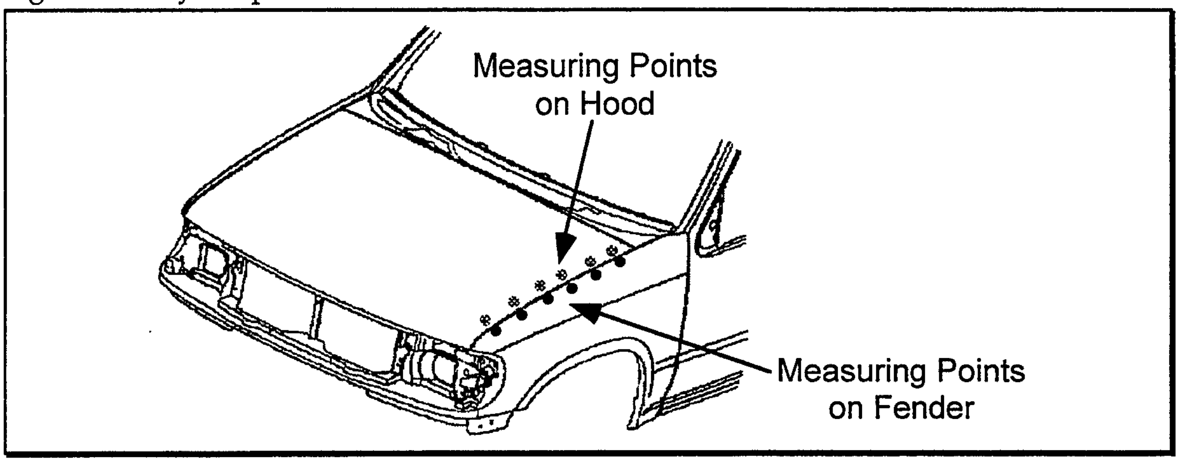


Figure 9-10. Example of Measuring Points located along an edge that is a KC.

9.4.2.1.3.Check Fixtures.

In order to show how a check fixture is coordinated with assembly tooling, Figure 9-11 shows an illustrative set of Master Locators and Measuring Points. A typical check fixture has a rigid frame and several "details," or rigid extensions spanning from the frame to the part. These details have at their end either locating features like pins, clamps, or surfaces, or a location for the measurement device to be placed when taking data.

Ford's suppliers and assembly plants utilize check fixtures at several stages in the fabrication and assembly process to monitor the product at each stage of production. The check fixtures locate the parts via their Master Locators and allow for data collection at the Measuring Points with minimal variation because measurements are taken at points located on the frame of the tool, defined in the global coordinate system. Check fixtures used by

[28] Ford acknowledges the goal of using the same locators in all steps in the process is not met in all cases

Ford's suppliers are certified by Ford for accuracy and compliance with the Master Locators and Measuring Points, so the assembly plant has faith in the data collected on these fixtures. At the assembly plant, check fixtures exist at each subassembly stage; though these are typically not used in production in day-to-day process monitoring, they are available and accurate for isolating problems during production ramp-up CA.

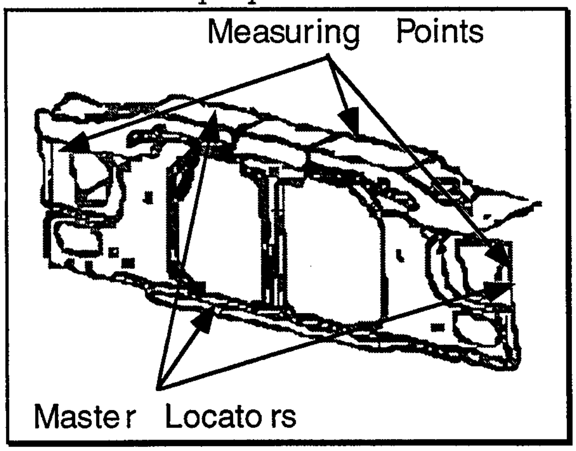


Figure 9-11. A representative set of Measuring Points and Master Locators on the Radiator Support

9.4.2.1.4.Statistical Process Control (SPC) Data.

The input for determining whether parts meet design intent is the *Measuring Point SPC data* from the supplier. Having data available allows this step in the investigation to proceed rapidly, in many cases in the minutes it takes to make a phone call. This is a key point in the comparison of the Ford and Vought processes: *if the data is available in advance, it saves time in the process.*

9.4.2.2. Information and Diagnostic Tools Accessed in Step 2 of Figure 9-9

Step 2 in Figure 9-9 also traces back to a common information data base through the diagnostic tools, via the dashed lines. The information and tools are described below:

9.4.2.2.1.Product Design Information.

Design information is readily available on a common CAD system, which contains the data for all parts, and locations of Master Locators and Measuring Points.

9.4.2.2.2.The Blue Buck.

As described above, the Blue Buck is the diagnostic tool for evaluating the product design. It is used during product development and launch to

identify design issues such as part interferences and misplaced features. The Blue Buck has the unique ability to eliminate the assembly process and tooling from the investigation by locating all parts in a common space, so the tools themselves are not required to create an assembly. Blue Bucks use the Master Locators to coordinate with the process and check fixtures. Figure 9-12 shows how the Blue Buck provides all the locators for the parts on a common Platform. Note that thelocators for the part in Figure 9-11 are the same as those used in the check fixture.

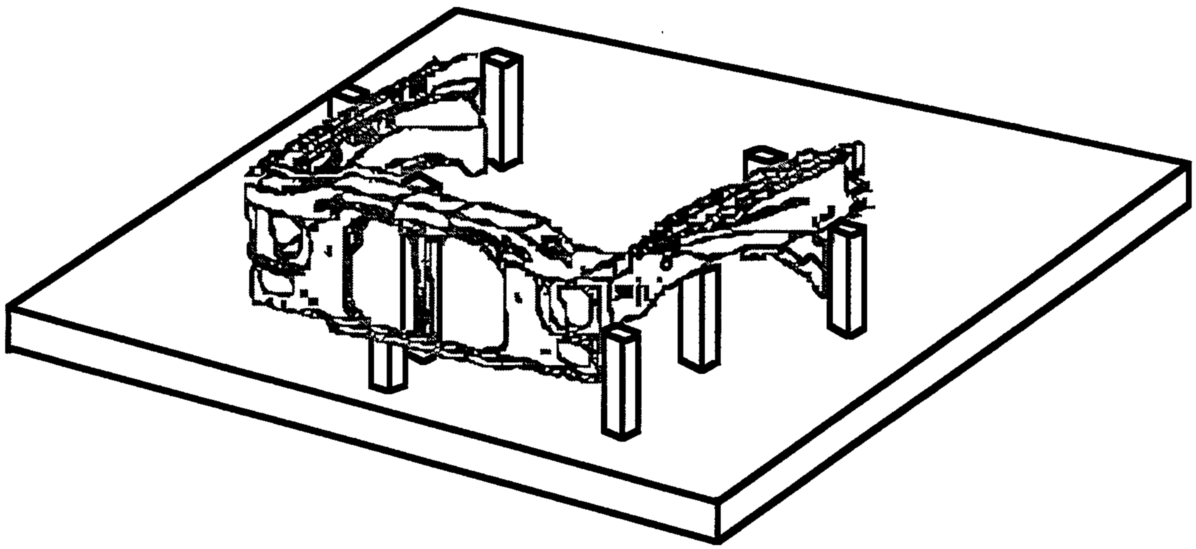


Figure 9-12. Schematic of a Blue Buck holding parts of the frame.

The Blue Buck provides investigators the ability to locate parts in space, fixturing at the same points used by the tools, and eliminates the effects of the assembly process from the picture. If these parts meet design intent, the Blue Buck in effect builds a 3D picture of the designed parts in space and points out design flaws. If an error is identified (e.g. two parts designed with mating features do not align correctly) in the Blue Buck, it is known to be either a design or quality issue because variations inherent to the assembly process and tooling have been eliminated by use of the Blue Buck.

9.4.3. The Origins of Critical Information and Diagnostic Tools

9.4.3.1. Process Used to Determine Measuring Points and Master Locators

Ford begins coordinating its web in the early stages of product development by following the process shown inFigure 9-13. These activities occur two or more years before production starts, and before tool design begins. As the part design evolves, Master Locators and Measuring Points are determined by "part teams" that include engineers, representatives from the Dimensional Control Group, the part supplier, and the tool and check fixture suppliers. The product of the process is a consensus book called the "LB-506,"

which contains part drawings that show the Master Locators and Measuring Points.

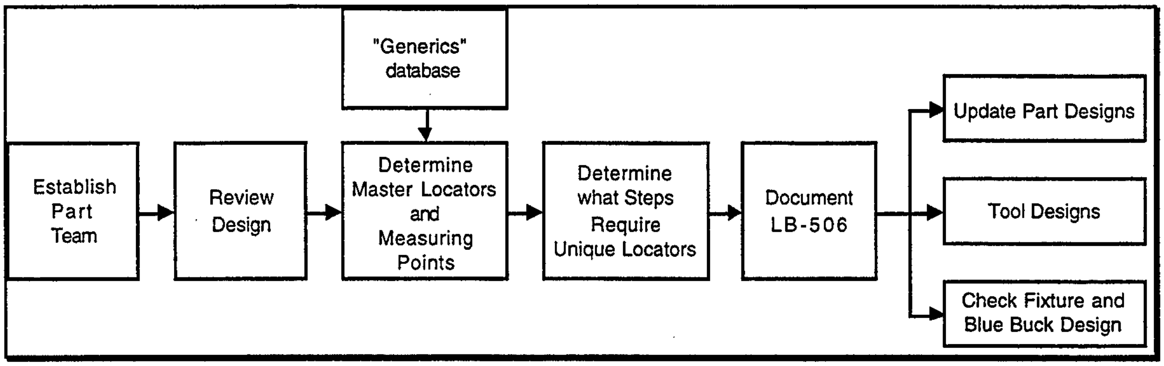


Figure 9-13. Process followed by part teams to establish Master Locators and Measuring Points.

The selection of the Master Locators and Measuring Points begins with a set of generic points for the part, which are classified down to vehicle type (e.g. small pick-up, large sedan, etc.) and part (e.g. outer fender, hood). These generic points are documented in the "Generics" books, which were created by the Dimensional Control Group based on

• points used on past vehicles. The team then develops the scheme for the particular model based on several issues, including[29]:

• access to the points during the process step; e.g. the new model has a part that covers the point before it is utilized,

• whether material exists in the generic location on that specific model; e.g the new model has a different shape that does not include a flange where a generic locator had been designated,

• preventing the point from being visible on the outside of the vehicle; e.g. the use of a generic point would leave a hole on the Fender in plain view,

• whether old tooling will be used, which may require the use of a Locator that already exists but may not be in the generic set,

• the need for additional points to hold the part, due to compliance, weight, etc., and

[29] Narendra Soman's research focus is selection of a sufficient and economic set of locators.

• whether the Measurement is KC on that model; e.g. if the KC does not apply on the new model, than there may be no need to designate Measuring Points on that feature.

The use of Generics gives a starting point for the part team on a new program and preserves the rationale for the selection of these points on past programs. The final set of points is often quite different than the Generics, so the process can not be simplified to the point that the coordination activity can be eliminated. The part team also determines when the same locators cannot be used throughout the assembly process and determine the additional locators required in these cases. The Master Locators and Measuring Points are documented in the LB-506 and product drawings, which are part of the common digital data base for each vehicle. They are then used to design the assembly and diagnostic tools used in the process.

9.4.3.2. The Origin of the CA Diagnostic Tools.

Like the Master Locators and Measuring Points, the important diagnostic tools are created during product development with the suppliers of these tools fully integrated in the process. The Blue Buck and check fixtures are built for use in pre-production development activities, such as fabrication and assembly of a test fleet of vehicles for road and safety tests. In this way, the tools that are critical to the process are developed concurrently with the product.

9.4.4. On-going Emphasis of the Process

Ford engineers are well prepared to conduct CA investigations using this process. All are trained in the 8D process in a course called "Prevent Recurrence." [Ford Interviews] Every engineer interviewed in the plant understood the need for the process and was well versed in it. In our opinion, there is employee buy-in and belief that the process has demonstrated utility because it eliminates the bias of opinion from investigations and utilizes data to classify the problems with great efficiency.

Ford management also emphasizes the use of the process and documentation of the results. During my visit to St. Louis during launch, a hectic period where schedule is tight and resources are limited, the plant management stressed the use of the process at each daily staff meeting. That the 8D process was emphasized at a time when one might have expected to hear, "I don't care how, just make the problem go away," was a clear indication of the belief in and on-going emphasis of the process at all levels of the organization.

9.4.5. Section Summary

Figure 9-9 shows that Ford's method quickly rules out possible categories of issues in a short time using the coordinated information and diagnostic tools, which are established as much as two years before, allowing the right people to focus on finding a solution in the remaining category of issues. Diagnostic tools are used to determine if a quality (part dimensions incorrect) or design (an error in the digital definition) error is the cause; if not the problem is classified as a tooling (assembly tool or process) problem. The method allows for a reliance on data in the investigation and prevents the team from being overwhelmed when attempting to identify a root cause from an unlimited number of possibilities. If the category can be identified quickly, non-value-added activities can be avoided and the investigation can be focused quickly.

This process is possible because Ford and its web perform a coordinated upstream set of product development activities to determine the Master Locators and Measuring Points for the parts. This information is then used to create the coordinated diagnostic tools that help classify issues and streamline the CA process. In the process, Ford gets the added benefit of having developed an organization that knows how to communicate efficiently despite its organizational and geographic dispersal. Finally, the process is followed rigorously, with employees who believe in the process, are well-trained to perform it, and have management that emphasizes its use.

9.5. Vought Corrective Action Process

This section describes observations of the corrective action (CA) process at Vought. Over the last several years, Vought has begun implementing several improvements to its design and manufacturing processes to update traditional aerospace practice to more contemporary quality practices. One such improvement is the implementation of Integrated Product Teams (IPTs) on all existing and new programs. A second improvement is a more structured method for performing CA in this IPT environment using a tool called Risk Analysis.

This section contrasts two methods of performing CA observed at Vought. First, the Risk Analysis is introduced, with strengths and weaknesses noted. The principal strength is that Risk Analysis provides a structured way to limit individual bias and build team consensus. However, this process relies mainly on the experience of the individual team members without a way to efficiently apply that experience to find the root cause and apply lasting CA. As described below, the time lag associated with this slow process often results in the incorporation of the work-around into the mainstream process because the long duration of investigations while awaiting data to determine the root cause results in other priorities taking

precedence before a true CA can be implemented. Second, the older method of CA that relies solely on the experience of one individual is described. This process represents a traditional approach to CA that seeks to eliminate problems quickly but does not include an investigation into the root cause.

9.5.1. The Formal Vought CA Process

Figure 9-14 shows the formal, documented Vought CA process. Above the dashed line in Figure 9-14 is a set of activities called the "Material Review," which is a set of activities to disposition the bad parts. The decision on the proper disposition of the non-conformance, either re-work or scrap of the bad parts, is formally assigned to group called the Liaison Engineering. These steps are handled separate from the CA steps shown below the dashed line. Vought has an efficient process to quickly disposition non-conforming parts.

Before the CA process outlined below the dashed lines proceeds, a fix must be implemented to contain the problem on assemblies until CA can be performed. This work-around may be determined by an individual or group, but in either case it represents an economical way to work around the symptom of the problem. In the cases observed during this study the work-arounds were typically a manual assembly task that added touch labor time on the assembly of the Inlet.

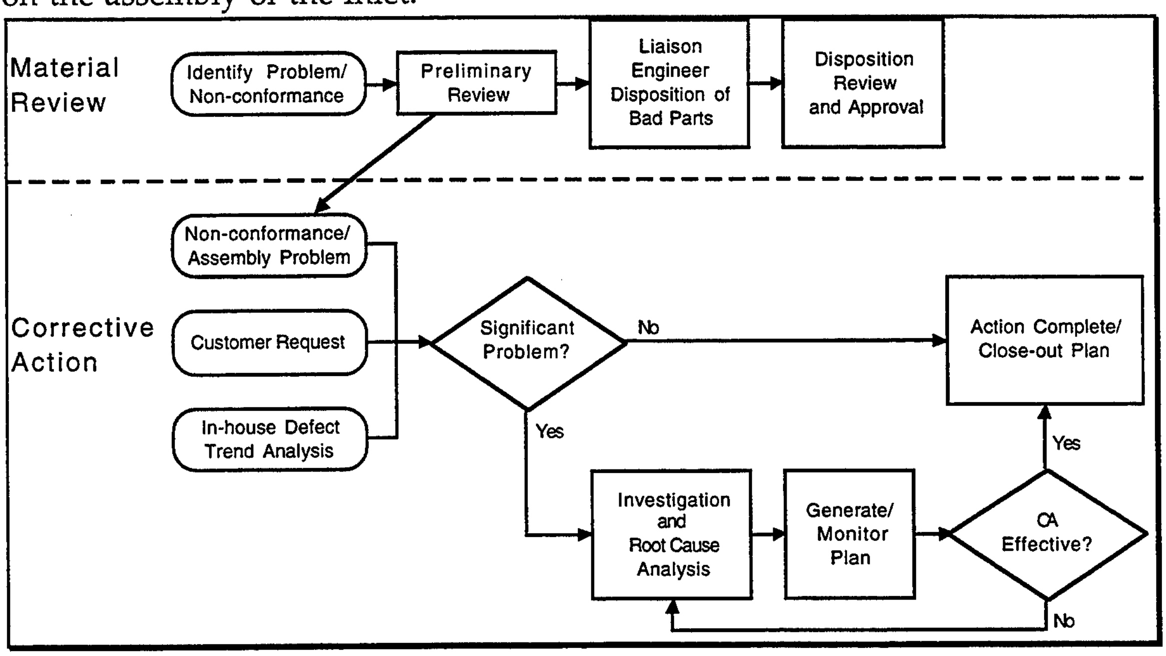


Figure 9-14. Formal Vought CA Process

CA is the responsibility of a CA IPT, a multi-discipline team that may further delegate responsibility to an individual manufacturing engineer or to a team of people. Figure 9-11 shows three ways the CA process can initiate: a

customer request, a defect trend analysis, or from a non-conformance. The following steps are conducted:

- the investigation and root cause analysis,
- generation of the Corrective Action Plan (CAP),
- monitoring of the plan,
- verification of the fix, and
- close-out of the CAP.

There is no formal documented method for determining a root cause. This study found CA investigations typically follow the two informal processes described in the sections below.

There is no one method used to investigate root causes. Vought's process relies on the experience of the individual team members to find a cause and a solution using the tools they choose. A review of the CAPs that were active during this study showed no two proceed exactly the same way, but some common steps were found depending on whether the investigation was conducted by a team or individual. The Inlet CA IPT consistently used the Risk Analysis on issues that occurred during this study, with very few recent investigations being assigned to one individual.

The CA IPT has representation from liaison engineering, manufacturing engineering, and product engineering. Representatives from procurement quality or one of Vought's fabrication shops attend meetings as necessary but are not assigned to the team. The problems that are deemed most critical, typically those for which the customer (e.g. McDonnell-Douglas - MDA) demands immediate results, become the issues that the whole team works on, while other problems are typically assigned to the individual manufacturing engineer to address.

9.5.2. The Informal Vought CA Processes

9.5.2.1. Investigation by a Team Using Risk Analysis

On the problems assigned to a group, the Inlet CA IPT tends to use the more systematic process called Risk Analysis, so this section focuses on analysis of this process.

9.5.2.1.1. Steps in a Risk Analysis

Figure 9-15 shows the steps used by teams conducting a Risk Analysis. After a work-around is put in place to contain the problem, the principal steps are:

1. Brainstorm Potential Causes. This step is accomplished by reviewing the features on parts that are located at the interface where the problem is located, and the steps in the assembly process that directly affect that interface, as described in the example below. It is important to note that *design errors* are not typically considered as possible causes when applying this method (see further discussion in Step 6 below).

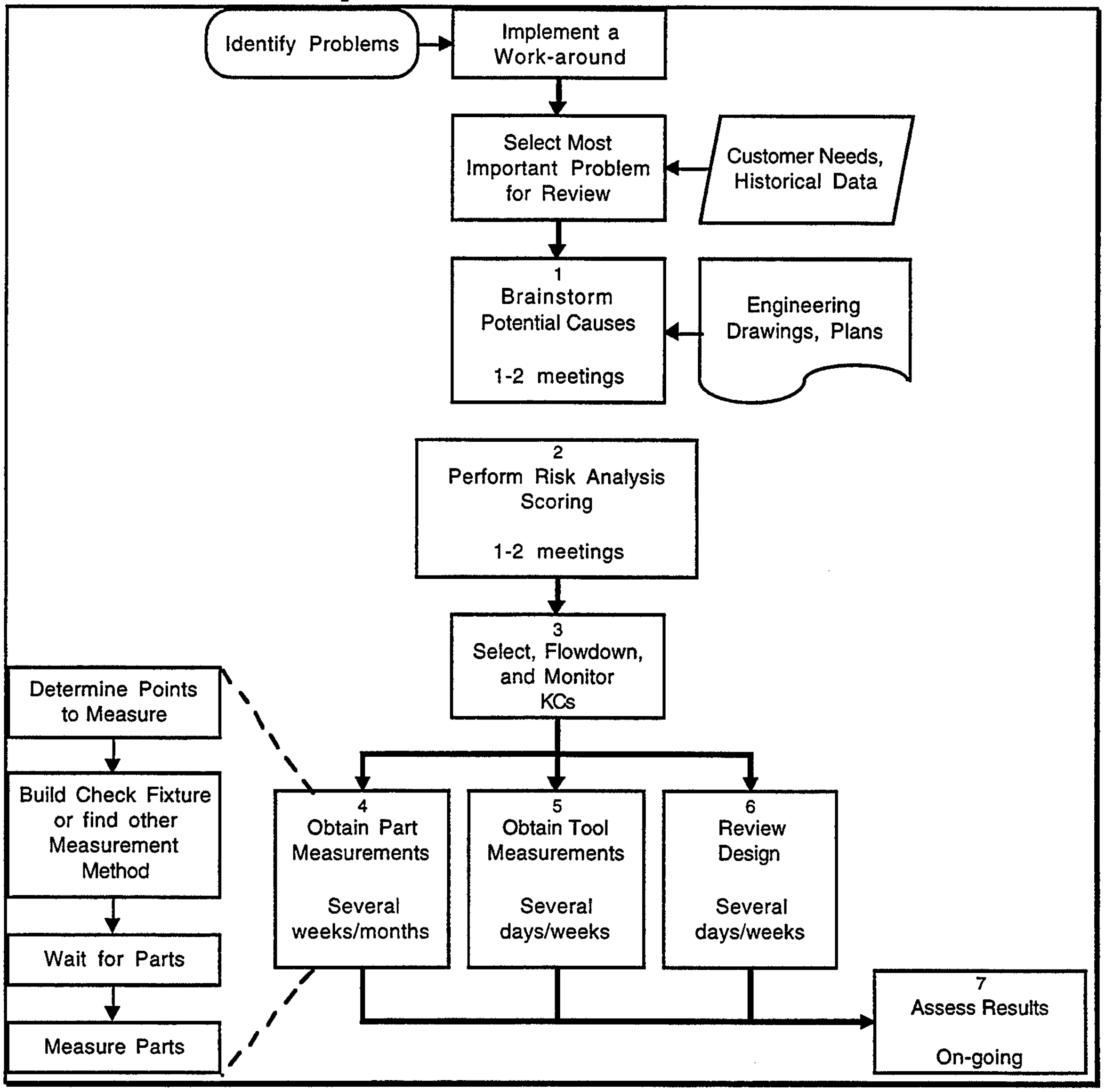


Figure 9-15. Steps in the Risk Analysis Investigation.

2. The Potential Causes are Scored. The central step of the Risk Analysis is scoring the potential causes on the basis of *occurrence, detectability,* and *severity.*[30] These scores are completed by the team and are based on company

[30] Occurrence is defined as how often the cause occurs. Detectability is defined as whether or not the cause would be noticed if it occurred. Severity is defined as the amount that cause would contribute to the problem being investigated.

guidelines (see Appendix B); a score is determined after team consensus [Vought]. The total score for the potential cause is the product of the three individual factor scores. An example Risk Analysis worksheet is shown in Figure 9-16.

3. The total scores are plotted on a Pareto Chart, with the highest scoring causes being selected as potential causes and warranting further investigation. Vought generally uses an "80/20 Rule" to identify the potential causes[31]; i.e. they look for 20 percent of the causes that make up on the order of 80 percent of the total score.

4. Obtain Part Measurements. Data is gathered on those factors that are identified as potential causes from the Pareto Analysis. Figure 9-15 shows the more detailed steps necessary to accomplish this. Vought does not have a check fixture readily available to measure the part, and has only limited measurement facilities that are dedicated to measuring parts to determine root causes, such a Coordinate Measuring Machines. Therefore, in order to get the data needed to assess what is the root cause, they first must design and build a check fixture for this purpose.

5. Obtain Tool Measurement. While part measurement investigations proceed, a tool check is typically accomplished. Vought has several measurement methods for

No.	Cause	Effect	Occurrence	Detectability	Severity	Total
1	Part A	interference	1	5	5	25
2	Part B	gap low	5	3	5	75
3	Part C	gap high	3	4	3	36
4	Part D, Feature 1	misalignment	10	10	8	800
5	Part D, Feature 2	gap high	9	8	10	720
6	Part D, Feature 3	gap low	7	1	2	14
7	Part E, Feature 1	overlap	2	5	3	30
8	Part E, Feature 2	scrap	4	1	4	16
9	Process Step 1	re-work	2	2	2	8
10	Process Step 2	misalignment	1	1	5	5

Figure 9-16. Sample Risk Analysis Worksheet

6. Review the Design. Concurrently with steps 4 and 5, a review of the design is typically accomplished. This step occurs too late to have design problems considered as potential causes up front in step 1 of the process, but this step does occur as a formality. Design errors are not considered to be likely potential causes for several reasons, including [Vought]:

[31] Vought designates these items Key Characteristics.

• the C-17 is considered to be a mature design, so MDA does not typically approve small design changes in hope of maintaining a consistent airplane configuration

• the drawings are on paper, not a CAD system, so analysis of the design is less automated and therefore more time-consuming.

7. Assess Results and Determine Root Causes. Based on the data that comes from the measurements of parts and tools, changes are made to correct the significant causes.

9.5.2.1.2.Risk Analysis Strengths and Weaknesses

Risk Analysis has two principal strengths when applied to CA:

1. Risk Analysis structures team consensus. In an IPT environment, Risk Analysis provides a structure to discussion involving people many disciplines. As discussed above, each item is scored in three categories that require concurrence among the team. If applied consistently, following guidelines like those in Appendix B, the process limits individual bias.

2. Risk Analysis provides a framework to consider many possible types of causes. Risk Analysis, when applied in an IPT environment, allows a variety of possible types of causes to be included, e.g. parts, process steps, etc. As opposed to brainstorming by one individual, which may be limited by experience, the Risk Analysis structure allows many types of problems to be raised and considered.

There are three weaknesses with this approach:

1. Risk Analysis is based on individual experience in lieu of data. Based on the guidelines for scoring, observation of the process, and personal study of the assembly problems, one must conclude that the scoring of the potential causes in conducting a Risk Analysis is dependent on individual experience, which still encourages bias in the system, though less so than when one individual investigates a problem. The amount of bias on the three scores varies; based on my experience with the Inlet IPT, the relative magnitude of opinion in Risk Analysis scoring is:

• Occurrence: medium to high. One would expect the occurrence score to be low if an accurate data base of past problems is available. However, an accurate data base requires the root cause to be documented after a problem is solved. Our study showed that the data base at Vought was not consistently updated following investigations to reflect the solution that was

implemented.[32] Some corporate memory is available, which can limit bias if the individual with the knowledge is part of the team. Usually, there is not an accurate way to determine the occurrence score for each potential cause

• Detectability: low. Detectability is attempt to determine whether sufficient visual or physical access to the part is present to notice or measure a discrepancy. For example, if the variation of a part feature is a potential cause, but if the effect of that variation would not be visibly noticeable, nor measurable, then its detectability score is high. The C-17 Inlet IPT appeared to have sufficient experience with the product to judge this score confidently and rarely was there debate of these scores.

• Severity: high. Without an analytical basis such as a detailed tolerance analysis to assess the severity of the cause, this is solely based on individual knowledge of the product and processes or judgment. Potential causes of variation are difficult to identify their impact is not obvious. The C-17 Inlet IPT often has to make this determination without the benefit of SPC data to assess the capability of the process, and does not have an analytical method or tool to determine if variation has a significant impact. This scoring appeared to be based solely on opinion.

2. Risk Analysis is better applied as a proactive tool. The risk analysis is a tool based on Failure Mode and Effects Analysis (FMEA) techniques. FMEA is intended to be used to assess potential causes proactively so off-line actions can be taken to mitigate the potential effects of that cause. It should be noted that FMEA is also used at Ford, but as a proactive problem prevention tool and not as a reactive tool [Prevent Recurrence]; Vought also uses Risk Analysis as a proactive analysis tool on its design programs [Vought]. In the uncertainty of a design environment, where a team seeks to mitigate potential problems, Risk Analysis provides a structured way for the team to apply past experience to a new design. In a production environment where a problem in fact does exist, it is preferable to apply a method that judges the product and processes themselves, based on data, than to brainstorm about potential causes based on judgment.

3. Measurement data takes a long time to gather. Vought does not have coordinated check fixtures in their manufacturing system, so the process of investigating parts often includes determining at what points and by what methods to measure a part, construction of check fixtures to gather the data, and waiting for parts to measure, as shown in Figure 9-15. In general, data is not taken in advance, so this measurement step rarely consists of simply gathering existing data. This time lag tends to aggravate the tendency to

[32] Vought has improved this practice since our study. It should also be noted that similar inconsistencies were found in the 8D data base at Ford. Both companies recognize that people often move on to the next problem without finalizing documentation of a problem just solved.

move on to new problems without follow-up on the original problem, leaving a work-around incorporated in the process.

9.5.2.2. Investigation by an Individual

9.5.2.2.1. The Experience-based Method

A practice identified as an improvement in the transition from "mass" to "lean" production is zero tolerance for defects in the system [Womack, et.al.] In traditional manufacturing firms, problems were handled by finding a way around them expediently to avoid slowing production; aerospace manufacturers are examples of this practice. In lean production, the need to eliminate these problems was recognized as a means to maximize the efficiency of the system. This transition is one in which Vought is progressing but has not yet eliminated completely. It is important to document this traditional method to assess the improvements that Vought has already made, and where additional improvement is possible.

Figure 9-17 shows the dynamics of the decision process associated with individual investigations. Usually, a manufacturing engineer is assigned the investigation. Depending on the skill level and base of experience that the individual manufacturing engineer has, some type of a work-around in the individual's area of expertise will be implemented. For example, an engineer with an experience base in assembly will usually try to fix the problem by changing the assembly process because this is the area of production in which he is most comfortable and familiar. Whether or not the actual root cause is a tooling or assembly process problem is not directly determined, and if the work-around masks the problem, then it is considered to have solved the problem.

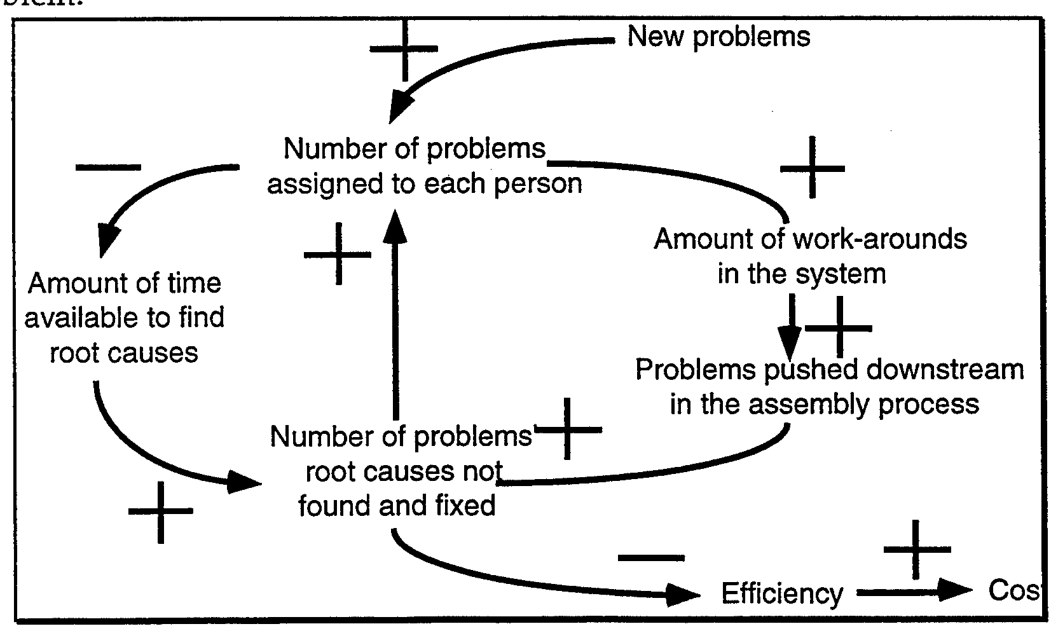


Figure 9-17. Dynamics of the experience-based CA process.

Unfortunately, problems that are "eliminated" in this way don't cease to exist. Instead, they reveal themselves in a different location. When that new location is further downstream in the assembly process, they become still more challenging to diagnose and more costly to fix.

There are practical reasons why the process has these characteristics. First, in the case of the C-17, the volume of issues has been large from the start of the program. This may be attributable to the lack of an integrated design process conducted by MDA resulting in a product that could not be manufactured economically.[33] With so many problems to solve, the manufacturing engineers have never focused on solving a small set of problems in a thorough manner. Second, the production rate on aircraft is so slow that new "big fires" are being investigated by the time an older problem reaches the monitoring stage. That is, because it takes a long time to get to the point of gathering data on an old investigation, and a work-around is in place to mask that problem, new problems have occurred that will require the effort of the CA IPT and little attention will get paid to the old problem. Third, the process does not include a method for classifying the problem early in the investigation, so with so many possible causes and no clear indication of where to begin, the manufacturing engineer's area of expertise is the readily available place to make a change and attempt to solve the problem.

9.5.3. Cost and Schedule Impacts of These Processes

9.5.3.1. Realization as a Measure of Cost

Realization rates in the aircraft industry are used to measure the efficiency of the touch labor applied to an aircraft against the allocated time for touch labor. Realization can be defined as:

$$R = \frac{Allotted\_Time}{Actual\_Time}$$

where allotted time is based on an estimate of the time needed to complete the task, based on industrial engineering experience in the plant, and actual time is the amount of time the task actually takes. Allotted time rarely changes unless the task changes. Actual time changes often based on worker skill (time generally goes down with experience), product maturity (workers come down a learning curve with experience on the specific

[33] The C-17 design began before Integrated Product and Process Design practices began in the aerospace industry. According to Vought and the Air Force, a set back of more than one year was directly attributable to a manufacturability negotiation among Douglas, Vought and other suppliers, and the Air Force to improve the ability to manufacture and assemble several parts of the C-17.

product), and number of work-arounds in the system (which drive actual time up since more work must be done).

Early in production, realization in aerospace can be far below .5, and some difficult tasks may never reach realization rates higher than .75 even after hundreds of aircraft are assembled, unless the allotted hours are changed to represent a difficult task or inaccurate initial estimate.

To illustrate the impact of incorporating work-arounds into the process, the illustration uses a realization rate of .6 to calculate the cost of incorporated re-work on the C-17.[34] Recall touch labor represents 30 percent of the cost of the airplane and the cost of the airplane is assumed to be $250M.

With these numbers, the cost of realization ($Cost_R$), defined as the amount the target cost is overrun due to realization less than 1, can be calculated as:

$$Cost_{Touch\_Labor} = 0.3 \times \$250M \times \frac{1}{R} = 0.3 \times \$250M \times \frac{1}{0.6} = \$125M$$

$$Cost_R = \$125M - 0.3 \times \$250M = \$50M$$

While this number is staggering, representing a cost impact of 20 percent, it is important to place the context of the number. It is not unreasonable to expect low realization numbers early in production because:

- touch labor, and therefore human learning, makes up such a large amount of the process,

- realization is based on estimated allotted times, which may be incorrect,

- each new aircraft brings about its own intricacies, so learning carried from other programs is limited, and

- the production rates are very slow early in a program (less than 1 per year), so learning is slow.

However, this study found that the work-arounds that cause low realization do not go away with time - *they become part of the process.* Figure 9-18 shows how a learning curve to reach a cost target can be adversely impacted by the incorporation of work-arounds, and hence cause an upward shift of the attainable cost target. This demonstrates that the incorporation of work-arounds as "corrective action" adversely affects the ability for the manufacturer to reach its cost goals.

[34] This does not represent the actual realization on this program.

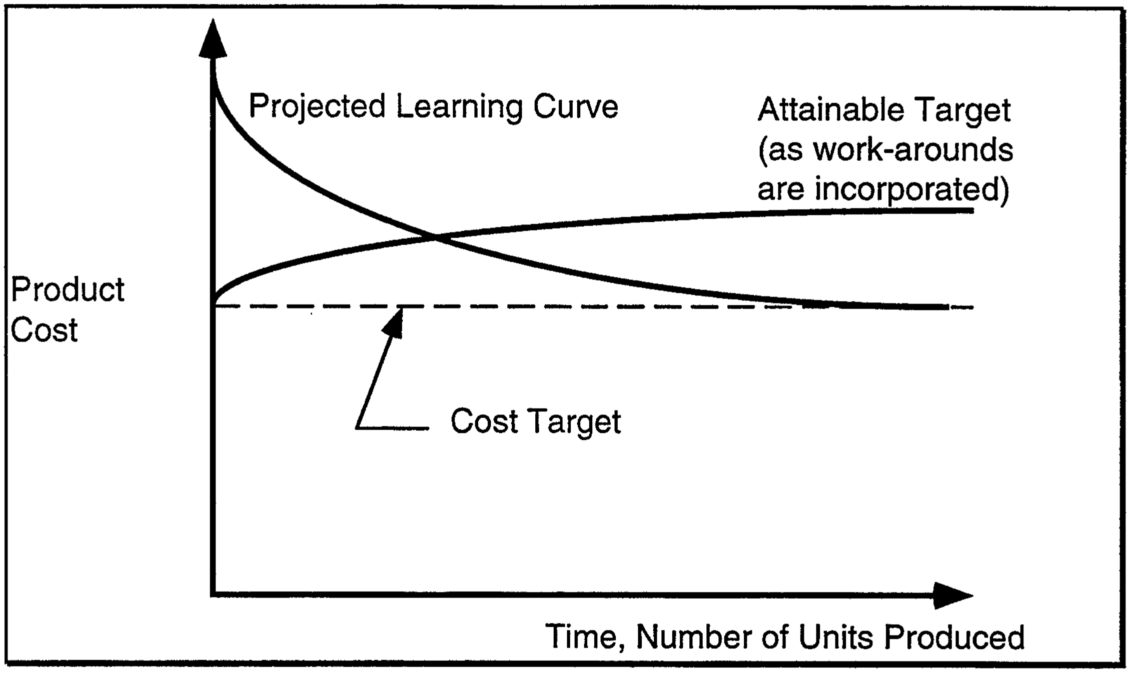


Figure 9-18. Effect of incorporated work-arounds on the attainable unit cost target.

9.5.3.2. Schedule Impacts

As shown in Figure 9-15, the major time lag in the CA process is the measurement of parts. It must be emphasized that this observation was not an isolated instance, but found to be typical on those investigations that remained on the agenda long enough for the construction of check fixtures and gathering of data.

The effect of this time lag is aggravated by the low production rates in aircraft, which have varied from 1 to 3 Nacelles per month over the life of the program. In this environment, it is typical for Vought to purchase parts in lots of 12 to 24, so an entire year's production of parts may be bought at the same time. When this is the case, there may be only one opportunity per year to measure incoming parts, and an improvement may not be implemented for another year beyond that.

This impact of production rate was thought by Vought to be the primary cause for the long duration necessary to conduct a CA investigation. Illustrating the magnitude of the time lag to obtain measurements for use by investigators is intended to show that this production rate is not just a cause, but a motivation that emphasizes the need for up-front measurement data to be used in CA. This need is the basis for the proposed method described in the Section 9.7.

9.5.4. Section Summary

Vought is an organization that is typical of those addressing improvements to older styles of manufacturing, where the impact of incorporating additional time in the assembly process is not fully appreciated. This occurs during CA investigations due to the long-duration of the investigations and the inconsistency with which CA is conducted. In some cases, CA is conducted by an individual, who typically solves a problem by implementing a work-around in his area of familiarity. In the more systematic team investigations that represent an improved approach, experience is still a major bias in the investigation, but the major contributor to the incorporation of work-arounds is the long period of time it takes to gather data and isolate root causes. Because Vought has limited check fixtures and little data gathering in their process, the data needed to conduct an investigation must be created before it can be analyzed, which can take many months or as much as a year, in this low production environment. The C-17 was used to illustrate the cost impact of this practice by demonstrating how the already large contribution of touch labor in aircraft assembly becomes a greater cost driver when more labor is added by incorporating work-arounds.

9.6. Strategies for CA Improvement

9.6.1. Current Production Programs

The IPT-based strategy at Vought described in Section 9.11 does not address an improvement method that should be used on existing production programs such as the C-17; instead it focuses on process for new programs. This thesis has shown that Risk Analysis has not proven to produce results in as timely fashion as Vought would like on existing programs, so other methods need to be considered. The range of improvement possibilities includes:

• at the most costly extreme, retroactively coordinating the entire manufacturing system by determining a master locating scheme consistent through all steps in the process and constructing check fixtures for all steps in the process, or,

• economically using existing equipment to develop a data base for CA investigations so the current method will proceed more efficiently.

It is unreasonable to expect Vought to accomplish the former because of the tremendous investment required and maturity of the program. Vought cannot adopt the Ford process directly because it does not have the diagnostic tools available to gather data as fabrication occurs and there are not sufficient funds to build check fixtures for all parts, those produced internally or those produced by suppliers. Without the check fixtures, Vought cannot get the

data needed to determine if the problem is a quality problem, which is the first category of problems Ford investigates. Vought needs a process that follows the intent of Ford's, but must eliminate the categories of problems other than quality first.

The available candidate is to eliminate tooling/process problems as a possible cause first. To do this, Vought will need to have readily available data when assembly problems occur. Vought can achieve this capability by following the steps discussed below, which begins with a study to better understand and refine its own processes. Once Vought has its processes well understood and refined, it can monitor its processes so data will be available at the time of an investigation. Then, when an assembly problem arises, Vought can follow the process shown in Figure 9-19. Like Ford's method, two questions need to be answered to determine in what category the problem falls. This process seeks to rule out tooling/process potential causes first, and design problems second, using data available from monitoring its processes.

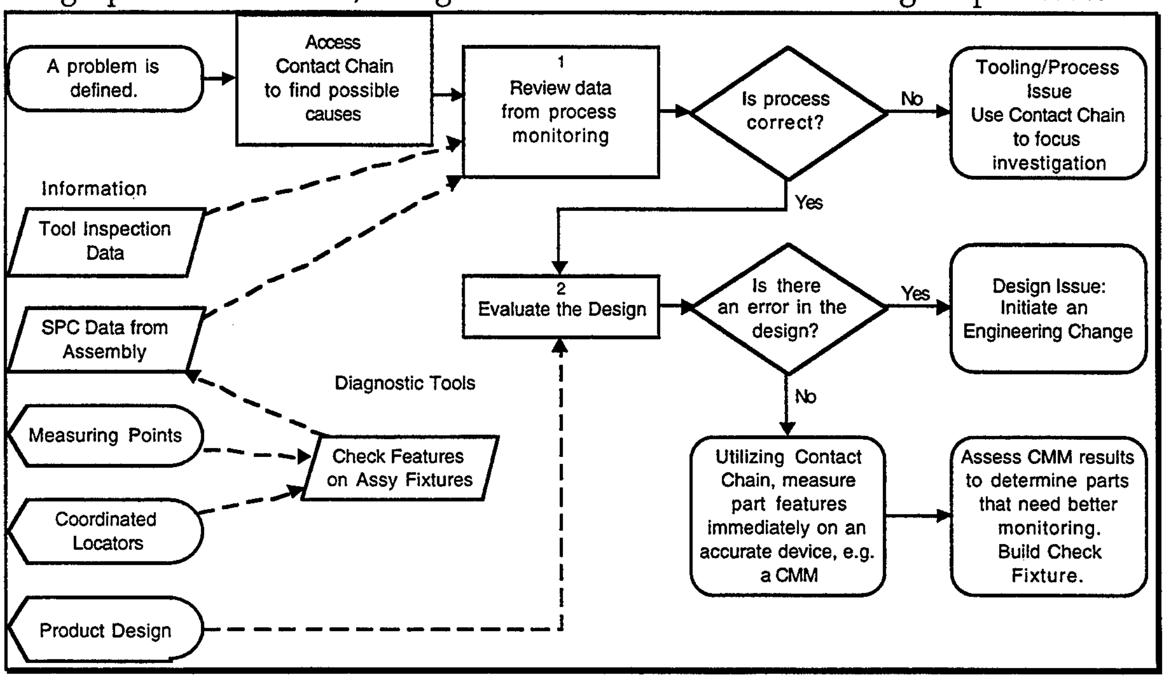


Figure 9-19. Proposed method for Vought to use on existing production programs.

There are several migration steps required to use this plan:

• To document its processes, Vought must begin with the high-level KCs and develop a view of all steps in the process that affect those KCs. The challenge is to identify only those parts and assembly tools and process steps that affect the KCs. Currently, Vought does this by brainstorming and focusing strictly on the parts at the interface, as shown in the Root Sum Squared study on the Joint 3 step in Section 9.5, Example 1. As described in

Section 9.2 and illustrated in the Contact Chain examples, other possible variation sources are not recognized in this manner. The Contact Chain captures these elements more systematically and presents them in a way that they can be understood across disciplines and organizations.

• Once Vought has documented its Contact Chains, it must seek to limit the number of contributing elements by better coordinating its locating schemes in assembly and sub-assembly fixtures. Every change in locating scheme is a possible variation contributor. The goal is to minimize the number of contributors that will need to be measured to minimize the cost of implementing this plan; by eliminating causes of variation, Vought makes this implementation more cost effective in addition to making their process better coordinated.

• Once Vought has refined its processes by coordinating its locating schemes, they should build measurement capabilities onto its tools to gather data about its process. While Vought personnel have stated that this represents a poor practice, "you don't use an assembly fixture as a check fixture because it takes up productive time in the tool," [Vought], this is the only economical way to build a data gathering capability into their system short of building stand alone check fixtures[35]. If these measurement capabilities lead to a more efficient process by eliminating some of the work-arounds in the system, the time expended in the fixture will be balanced against improved efficiency in the process. The Contact Chains will indicate which fixture features and process steps need to be monitored.

Once these tasks have been accomplished, the process in Figure 9-19 will be achievable. The steps in this process are:

1. When a problem arises, the data available from process monitoring and data from Vought's tool inspections can be the first thing considered to review if the assembly tooling or process is the potential cause.

2. If not, Vought reviews the design for a possible error (as mentioned in Section 5, this is not often the case on existing programs).

3. Finally, if neither proves to be the cause, then a quality problem is the cause. Vought can use the Contact Chain to help determine which part features are potential causes and limit the number of parts they need to investigate. Instead of waiting for check fixtures to be built and risking not having parts available to measure at that time, Vought should immediately measure parts on the most accurate measurement system available. One example is the use of Coordinate Measurement Machines, which Vought has available in its plant but not dedicated to supporting CA investigations.

[35] This continues to be a debate at Vought, but the trend, as demonstrated in Section 5, has swung toward Vought being willing to sacrifice time in the fixture to gather data.

9.6.2. Illustration of the Proposed Process for Current Production Programs.

Joint 3 was described in Figure 9-7. The following describes how Vought would apply the new strategy to Joint 3:

•Document the Contact Chains - see Figure 9-8.

•Refine its process to eliminate sources of variation where possible. Figure 9-20 shows

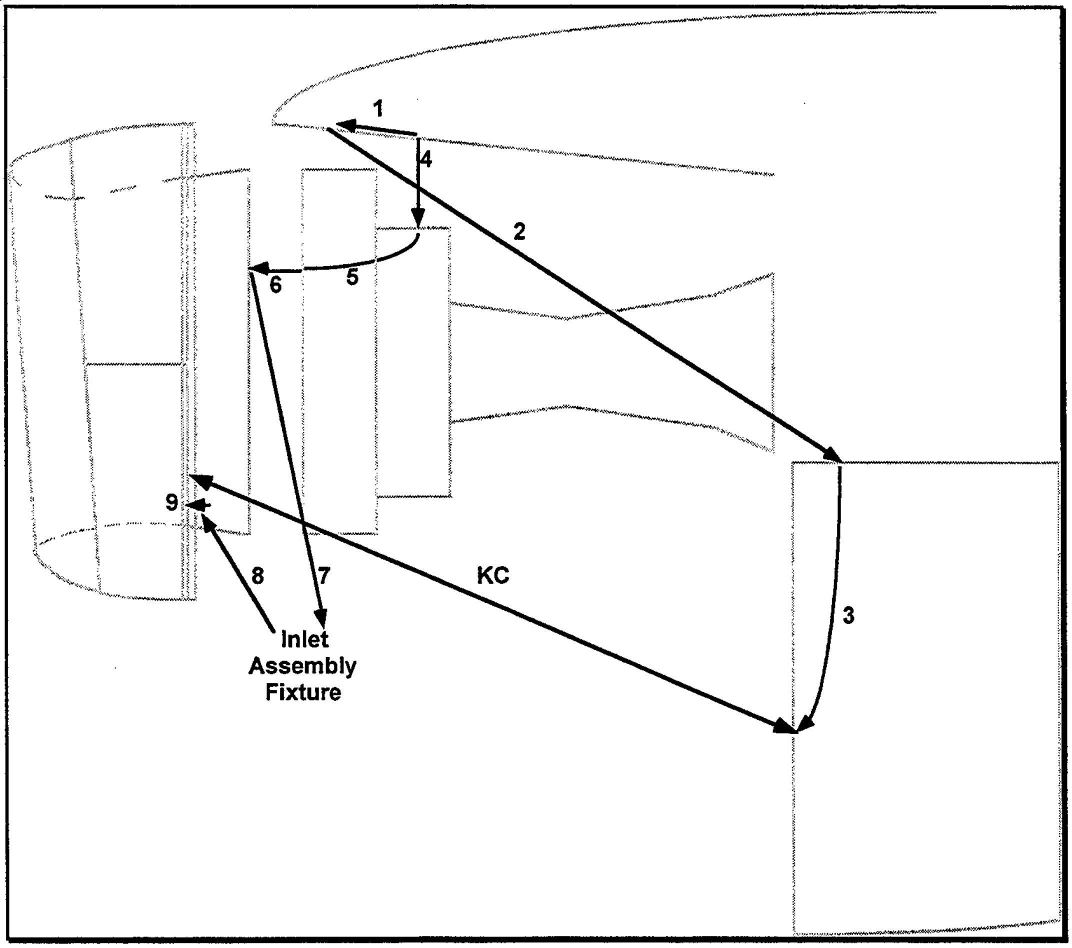


Figure 9-20. Refined Contact Chain for C-17 Nacelle Joint 3 gap.

a new Contact Chain for Joint 3 that would require a change in the Inlet Fixture. If the Inlet Fixture locates the aft edge of the Cowl Skin and pushes the variation forward, as opposed to locating the Lip in the fixture and locating the Cowl Skin relative to the Lip, the Contact Chain is reduced by four steps, and two sub-assembly fixtures are eliminated. By eliminating these fixtures, Vought avoids the need to build a check fixture capability on these fixtures. Only one fixture requires a checking capability - the Inlet Fixture (which in this case is already available). The new chain includes:

1. the dimension on the Pylon between the points that attach the Accessory Door and the points that attach the Engine

2. the interface of the Accessory Door and Pylon

3. the dimension of the Accessory Door from its attachment points to the Pylon to the edge that interfaces with the Cowl Skin

4. the interface of the Pylon and Engine

5. the dimensions of the Engine

6. the interface of the Engine and Engine Ring

7. the interface of the Engine Ring and Inlet Fixture

8. the dimension of the Inlet Fixture between the Engine Ring locators and Cowl Skin locators

9. the interface of the Cowl Skin to the Inlet Fixture.

• Gather data on the fixture and process steps. The refined Joint 3 Contact Chain requires Vought to monitor the accuracy of the locating features for the Engine Ring and Cowl Skin on each assembly. Vought would need to attach the means to monitor these process steps to the Inlet Fixture, and would need to gather data in a consistent manner.

• In addition, Vought needs to obtain data from the Engine and Pylon manufacturers on their links in the Contact Chain. Figure 9-21a shows how the suppliers are currently tiered, and Figure 9-21b shows how the data needs to flow to enable Vought to be prepared to investigate assembly problems for Joint 3.

With these tasks accomplished, an investigation following the process in Figure 9-19 would proceed as follows:

1. Assess the data from process monitoring to determine if the assembly process or fixture is the cause.

2. If not, review the design for a possible error.

3. Finally, if neither proves to be the cause, then examine the following part features as expeditiously as possible:

• the dimension of the Accessory Door from the edge to its attachment points to the Pylon

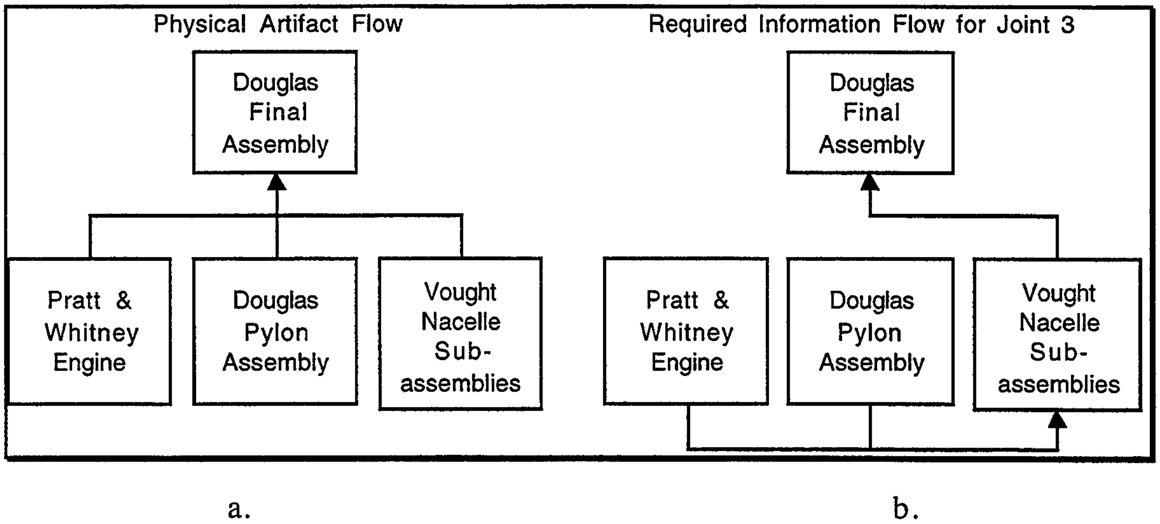


Figure 9-21. Flow of assemblies (a) and required data flow to support investigation of problems at Joint 3 (b).

- the dimension on the Pylon between the points that attach the Accessory Door and the points that attach the Engine

- the dimensions of the Engine

9.6.3. New Programs

Section 9.3 discussed how Vought and other aerospace companies have implemented more proactive upstream design process to prepare for data collection during assembly. Because of the large volume of Measuring Points that are required to monitor a product as large as an airplane, Vought's plan calls for the designation of KCs as the points that will be measured to keep the system economical. This new approach is being applied on new programs. Only limited results are available to date; however, even with a focus strictly on KCs, indications from the industry is there are still "too many points to measure" and therefore process monitoring continues to take low priority in aircraft manufacturing.[36] Ford's method of classifying problems forms an excellent basis for aerospace companies to understand the value of following through with its upstream planning. These is an economic trade-off between a low-risk approach that requires building check fixtures in advance, versus a high-risk approach that saves building check fixtures but has proven to result in on-going CA during production. Ford has made a decision in favor of the low-risk approach, aerospace companies have yet to be convinced that this is the correct approach.

[36] A similar process with similar results has been noted at the Boeing Corporation.

Figure 9-22 shows how the addition of the Contact Chain can further streamline this CA process by focusing investigations that reach the stage where the problem has been classified as a tooling issue - noted in the last step in the process. Recall that Ford and Vought do not currently have a way to identify potential root causes systematically for these types of problems. The additional step in the process is simple in that the Contact

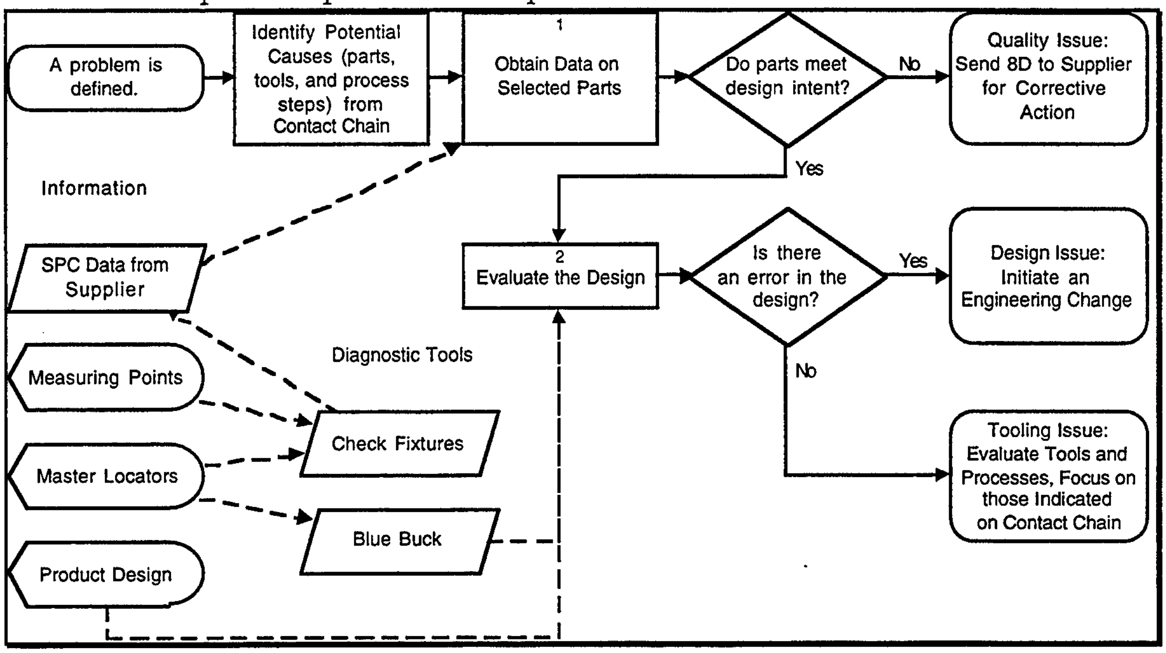


Figure 9-22. Proposed improved CA method for Ford and Vought to use on new production programs.

Chain forms the basis for which tooling features and process steps should be investigated first for tooling problems.

9.7. Skills Needed and Organizational Issues

In order to conduct more systematic CA investigations, Vought requires additional skills. First, more system-level understanding of its processes by a wider group is necessary to identify the parts, tools, and processes that contribute to its KCs. Second, it must improve its coordination of fixture locators through the entire process.[37] Third, it must be able to recognize where the excess sources of variation exist in loops like those eliminated between the Contact Chain in Figure 9-8 and Figure 9-20. Finally, Vought must continue to expand its interaction with suppliers to obtain input and consensus on how locating schemes can best be coordinated, and must find the contractual arrangements that will support this effort.

[37] Vought and all other major aerospace companies have recognized this as a weakness in their traditional processes.

In addition to training, the organizational issues discussed above also must be addressed before the process can be improved. These issues go beyond Vought, as it is just one member of the web that must be willing to broaden its view of the roles of organizations, as illustrated in Figure 9-10. Within Vought's control is the ability to coordinate the web members that come under Vought's authority.

9.8. Section Summary

This Section compared the corrective action strategies of an automobile company and an aircraft company. The automobile company appeared to have, as of the date of our study, the more systematic approach. It was designed to eliminate personal opinion by using a cross-functional team and the same 8 steps every time. It relies heavily for its success on having created a large amount of assembly-level documentation well before production begins.

This Section also showed how the contact chain could be the source of an improved CA method at both companies. The Contact Chain is a tool that communicates several types of important system-level information in a simple form that can be understood across disciplines. Documenting Contact Chains forces in-depth understanding of a process and reveals the true contributors to tolerance stack-up. The Contact Chain can reveal all of the following:

- the organizations that lie in the chain to deliver a KC

- the process steps, tools, and part features that lie in the chain

- the effect of assembly sequence of which parts and tools contribute to tolerance stack-up

- the items that need to be included in a simplified tolerance model.

10. Aligning Technical and Organizational Aspects of Complex Manufacturing Systems[38]

10.1. Managing Flexibility

This section of the report addresses the problem of improving the first-time success of new manufacturing systems by providing a method for concurrently designing its technical and organizational components. The method is described in the context of emerging flexible assembly methods in the aircraft industry.

In today's competitive environment, companies are increasingly looking to introduce more products in shorter periods of time. To deal with these new pressures, many corporations are aggressively pursuing flexible design and manufacturing strategies. In some industries, a suitable flexibility strategy might involve the design and production of modular components that can be assembled in any of several different combinations. Nippondenso, for example, designs flexibility into their products by carefully managing the interfaces between modular components. [41] Levi Strauss also pursues a similar type of `mass customization' strategy. Each customer can be measured in the store, and the closest of over 8,448 different possible jean templates is then used to create `custom made' jeans. [14]

The degree and type of flexibility sought by companies varies depending on the competitive forces in their particular industry. In the production of aircraft structures, for example, obvious cost issues prevent Boeing and Airbus from developing an aircraft structure customized for each customer. The final aircraft, however, can be customized for different customers. TWA, for example, may want to have more Coach or First Class seats than other airlines. To provide this flexibility, aircraft are designed to accommodate many different seat types and configurations. The degree of flexibility is limited, however. It is extremely rare for an aircraft structure to be designed to accommodate two different types of wing or fuselage.[1]

Despite the inflexibility in the design of aircraft structures, there are ways in which the production of these structures can be made more flexible. At present, most large aircraft structures are assembled using large, dedicated fixtures. These fixtures can only be used to produce a specific structure, take several months to build and can cost anywhere from a hundred thousand to a million dollars. In order to be able to increase the production rate of an aircraft, an adequate number of fixtures is needed. Because of the cost and floor space requirements of current fixtures, it requires great effort and dedication of resources to have the capability to rapidly increase production.

[38] This section is based on "Aligning Technical and Orgaizational Aspectsof Complex Manufacturing Systems," SM Thesis by Tariq M. Shaukat, MIT Mech Eng Dept, Feb, 1997.

To solve this problem, many aircraft companies are trying to change the nature of aircraft assembly. Instead of using the dedicated fixtures, there is an attempt to use flexible fixtures and, in many cases, to eliminate the fixtures all together.

The elimination of fixtures allows the aircraft manufacturers to develop capacity flexibility. However, making the changes in technical features required to eliminate fixtures is not enough. If the organization is to remain aligned with the new business and manufacturing strategies, changes in the organizational structure must be made. Factors that must be addressed include organizational learning, continuous improvement, skill and responsibility requirements for factory floor workers, and the establishment of new information pathways.

10.1.1. Organizations and Technology

About 30-40% of attempts to increase manufacturing flexibility fail. [4] While some of the reasons for this high failure rate are purely technical, the majority of failures are due at least in part to other factors. Some failures are the result of managers not understanding exactly what kind of flexibility they need to achieve their strategic goals. In other cases, the workers and support personnel do not have the skills necessary to properly use the advanced manufacturing technology in the flexible systems. In still other cases, the organizational structure of the firm inhibits the smooth operation of the manufacturing system. [39]

Most of the causes for the failure of advanced manufacturing systems stem from an incompatibility between the technical and the organizational systems within a firm. Here, elements of the organizational systems include the workforce management system, continuous improvement activities and infrastructure, the supply chain, and communication flows. An example of an incompatibility might be that workers are not given the roles and incentives necessary to promote the necessary communication flows.

In most cases, a great deal of time, money and effort is spent on the design of the technical elements of a system. Little effort is spent on explicitly designing the organizational system. If an effort is made to design the organizational system, it is most often independent of the technical development effort. The result is a manufacturing system with incompatible components. Leonard-Barton points out that "a technology almost never fits perfectly into the user environment." [22] Building upon this point, Tyre notes that "Successful technological change also requires active organizational efforts to adapt the new technology, the existing manufacturing system, and the organization itself to a new set of demands." [36]

To successfully implement new technologies into a manufacturing environment, **the technical and organizational systems must be designed concurrently**. The concept of concurrent engineering must be expanded from simultaneous technical development of the design and manufacturing systems to the development of the total design and manufacturing system. In this latter case, worker roles and skills, supply chain structure, communications flows, corrective action and continuous improvement processes would all be considered at the same time as the accuracy of the machine tools and the design of a product's components.

The research described here provides an initial framework for aligning the technical and organizational aspects of complex manufacturing systems. Using and building on this framework will allow firms to improve the first-time success of new manufacturing systems, and to improve productivity and process improvement on both new and existing programs.

10.1.2. Learning Across Organizational Boundaries

While the role of organizational structure in manufacturing systems is perhaps not questioned, the subtleties of its role are not widely appreciated. In most manufacturing environments, for example, the organizational structure is of secondary importance to the technical system. Yet, it is through the organizational structure that many of the most important elements of a manufacturing system are affected.

Learning is a case in point. Companies are increasingly discovering that learning is a major source of competitive advantage in today's business environment. There are numerous stories where a company that was doing poorly recovered and excelled by transforming itself into a "learning organization".[2] Books professing to teach companies how to become "learning organizations" are very popular, as evidenced by the success of Peter Senge's The Fifth Discipline. [28]

There are several elements to any learning system. Some of these are shown inFigure 10-1. First and foremost, people have to want and have the opportunity to learn. The environment in which the people find themselves is therefore extremely important. A company which provides the motivation, training and time - the corporate values - necessary for learning to occur has a much better chance at being successful than one that takes learning for granted and does not provide the proper environment. However, building this environment is not enough. In order for the maximum amount of learning to occur, the system needs to be designed to facilitate information and communications flows.

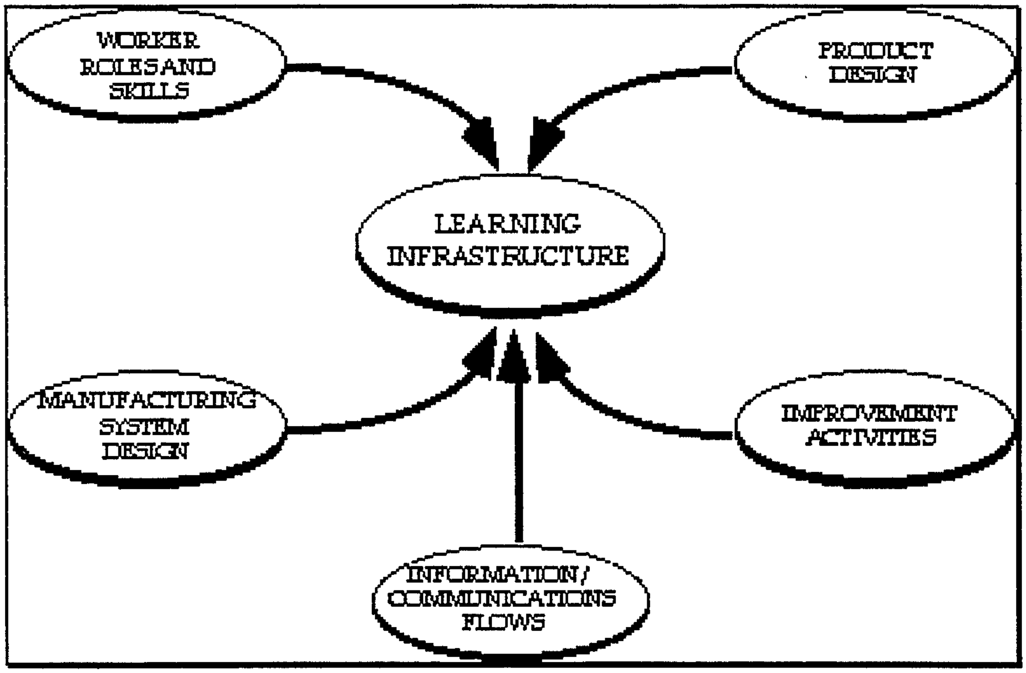


Figure 10-1. Elements of a Manufacturing System's Organizational Infrastructure.

Several studies [30] have noted that "all learning depends on feedback".[3] Feedback can occur in two ways. It occurs to some extent through the natural process of doing things. If you drill a hole, you learn something about how well you drilled it. This is a direct form of feedback. There is also an indirect form, in which information ripples through the entire system. Exactly how the feedback progresses through the system depends on the communications infrastructure present. To achieve the maximum amount of learning in a manufacturing environment, this infrastructure must be specially designed; it is not enough to accept the infrastructure that is created as a by-product of other decisions.

Creating this infrastructure is not easy. Elements of the infrastructure are dependent upon the technical features and capabilities of the system, the corporate culture, past and present organizational structure and the design and capabilities of the supply chain. Links must be created to span these and other factors. In order to avoid the waste of resources, links that do not need to exist should not exist. At the same time, any links that might be important should be checked to avoid overlooking an important factor.

Addressing the problem of designing and creating this infrastructure is one of the major themes of this thesis. The goal, alluded to above, is to improve the learning and improvement capabilities of firms, and particularly to improve the first time success of new manufacturing systems.

10.2. Process Interactions Matrix

An extension of the Part Interactions Matrix, called the Process Interactions Matrix (PIM), has been developed in this research to document the structure of manufacturing systems. In a PIM, the steps of a manufacturing process, along with their interactions, are recorded. An interaction occurs whenever what happens in a given step affects another step in the past or future. For example, if a part that was put into place in one step has to be slightly moved for another part to be added, an interaction would be noted. Similarly, if the location of a part, B, is set by the location of another part, A, the step at which the part B is located is connected to the step at which part A is located. Any error in locating A will necessarily result in an error in B's location.

The general principles of the PIM are similar to those for the DSMs described in Section 3.3.1.1. There is, however, one important difference. While the order of tasks in a product development process or the members of teams can be changed quite easily, changing the order of tasks in a manufacturing process is much more difficult. In an assembly process, for example, the sequence is set by other factors such as precedence relations, tolerance propagation consideration, and physical proximity of the equipment and parts.

Given this constraint, the PIM cannot be used alone to optimize manufacturing processes. Instead, the value of the PIM derives from its ability to convey important information about the technical and organizational aspects of manufacturing systems. While the technical system cannot be optimized, many operational aspects can.

10.2.1. Reading a Process Interactions Matrix

Figure 10-2 shows an example of a PIM for a general manufacturing system. Each row of the matrix is assigned a particular step in the manufacturing process, as is each column. First, the rows and columns are grouped by organization. In the figure, they separated into fabrication and assembly groups. In a detailed PIM, these groups would be broken down further into particular processes and subassemblies. The rows and columns are then arranged so that the process steps are in the sequence in which they occur within each particular process. Once arranged, the diagonal should represent the cells of the matrix where the steps on the rows and columns are the same.

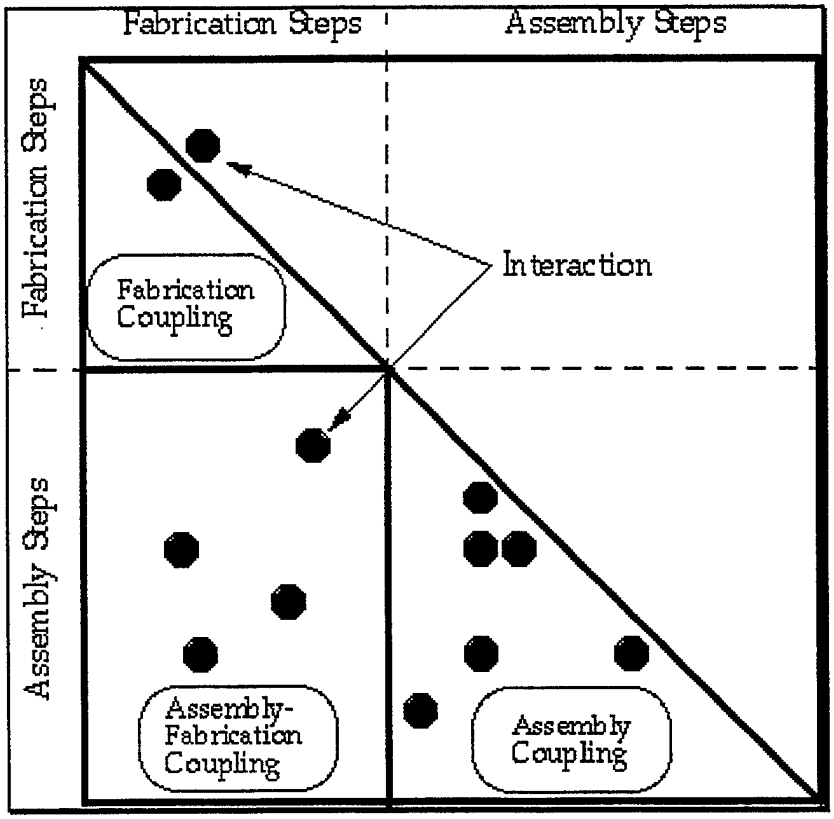


Figure 10-2. An Example of a Process Interactions Matrix

Interactions between different steps can be noted once the basic matrix structure is complete. Interactions are those events that affect the outcome of a particular step. A particular step, Y, might affect the outcome of another step, Z, but the reverse might not be true. When an interaction occurs, it is noted on the matrix; in the figure, the circles represent the interactions. Each column represents a possible interaction, whereas each row represents the step of interest. For example, if there is an interaction in row j, column i, this means that step i interacts with step j, i.e., i affects the outcome of step j. By looking down a particular column, one can tell how much a particular step interacts with other steps. Looking along a row shows which and how many other steps affect the step assigned to that row.

Because of the nature of the interactions, the matrix is normally not symmetric. In fact, if the steps are arranged in strict chronological order, it is likely that there will be few, if any, interactions in the upper triangular region.

The figure is divided into three main regions. Each of these regions represents a different type of interaction block. Whereas the term `interactions' is used here to represent the linkages between individual steps, `coupling' is used to denote types of possible interactions. The `assembly coupling' region, for example, shows the area of the figure in which assembly

steps might interact with each other. Similarly, `assembly-fabrication coupling' denotes the region where assembly steps might interact with steps in the fabrication process.

10.2.2. Creating a Process Interactions Matrix

Process Interactions Matrices combine three types of information - process sequences, `physical' interactions from a contact chain, and `service' interactions from organizational maps. The process of constructing a PIM involves several stages:

Identify the organizations which contribute to the manufacturing process, including internal and external suppliers and maintenance, engineering and other support elements.

Document the tasks through which the product is produced. The tasks should be grouped by the organization responsible for them, and should be recorded in the order in which they are completed.

Understand the Key Characteristics and create the Contact Chains for the system. Use this information to understand how the steps in the process interact. Further review the system, talking to indirect and direct workers, to gain a more complete understanding of the interactions. If a process does not yet exist, imagine the process in operation.

Understand the interactions. This is the step at which the semantics of the system become completely defined. It may or may not be necessary, depending on the goals of the user. Further details on this step are presented in Section <u>4.6.7</u>.

Once a PIM is constructed, a great deal can be learned about the technical and organizational aspects of the manufacturing system. The uses of the PIM are described in the sections below.

10.2.3. Communications Flows

The most direct use of the PIM is in understanding the communications flows that must occur within a system in order for it to operate efficiently. All learning in any system occurs as a result of feedback. Interactions represent potentially valuable feedback channels. The ability of an interaction to stimulate learning is determined by the speed with which relevant information is conveyed.

Whenever an interaction occurs within a team boundary, learning can occur at a rapid pace. The feedback is immediately available. However, when the interactions transcend organizational boundaries, learning is much more

difficult. In these cases, an organizational (communications) infrastructure must exist. The purpose of this infrastructure is to reduce communications delays, providing timely feedback to allow learning, and therefore process improvements, to occur.

Of course, not all interactions are equal. Just as in any process improvement activity, the processes which will have the highest impact should be improved first. Identifying the important interactions is a matter of understanding the structure and semantics of the system. Interactions which fall within a KC Realization chain (i.e., the set of steps that affect the step at which a KC is realized) have a greater effect on the outcome of the manufacturing process than those that are not. Interactions in the KC Realization Chain represent higher leverage areas for improvement activities.[2]

10.2.4. Process Architecture

Products are often categorized by their architecture. They are described as being either modular or integral. A modular product is one in which parts have minimal interactions with each other. All interactions occur through standard interfaces. In a modular product, individual parts or subsystems can perform their functions independently of each other. Conversely, an integral product is one in which several or all of the parts share functions. The success of the product depends upon the performance of the system as a whole. [37]

Process architecture is a concept similar to product architecture. Processes can be categorized as modular or integral. A modular process is one in which there are few interactions between the process steps. Of course, there are different shades of modularity. No process is ever completely modular, and few processes are completely integral. Nevertheless, the distinction is a useful one when thinking about processes.

Both types of processes present opportunities for learning. However, in a modular process, the learning is limited to each individual step. In an integral process, on the other hand, learning happens on several different levels. As in the modular case, there is learning at the individual step level. Unlike the modular case, learning in an integral process is also possible at an organizational level. At this level, a deeper understanding of the system is gained, resulting in increased opportunities for learning. The amount of learning that actually occurs is a function of several variables, including the time it takes for information to travel from one organization to the other, the roles of the work teams, the skill level of the team members, and the clarity of the relevant chains.

10.2.5. Defining Worker Roles

Process architecture has a number of other consequences throughout a manufacturing system. One area in which it is particularly important is work design. For the most part, work teams have been created without analyzing the detailed technical requirements of the system.[3] However, an understanding of the technical requirements is critical if the team boundaries are to be drawn correctly. The PIM and process architecture framework described here allow us to easily incorporate technical considerations into the design of work teams. The learning issues presented above provide a guide for work team design. In order to have the maximum amount of learning in a manufacturing system, communication times should be minimized. This is best accomplished by making a small team responsible for all of the processes that interact with each other. That is, clusters of interactions should be internalized within a work team whenever possible, much as design teams were created based on interactions in the Part Interactions Matrix. [35]

There are, of course, constraints upon worker roles imposed by the physical location of equipment and organizations. Trade-offs must be made between learning efficiency and operational efficiency. If this were not done, the time and money saved through increased learning would surely be spent in travel time! However, just as worker roles would not be defined without thinking about the proximity issues, they should not be designed without some attention to learning opportunities.

The other effect of process architecture in workforce management is in the identification of worker skills. As mentioned in Chapter 3, competency is a function of both roles and skills. As we define the role of a worker, we also define the skills that worker needs to be competent at their job. In general, the more integral a process, the greater the level of macro-skills needed to effectively perform the job. The more feedback loops that are present, the more a worker needs to be able to think about the system as a whole. The worker also needs greater communications skills in order to be able to operate in the complex organizational infrastructure. Micro-skill requirements are generally the same as in the modular case - they are defined by the specific tasks (e.g., drilling, riveting, placement, programming) and do not depend to a great extent on the interconnections.

10.2.6. Make-Buy Decisions and Supply Chain Management

The discussion of work team design naturally leads into another, broader topic, that of supply chain design and management. Like product architecture, process architecture is important when making make-buy decisions. As the case study on the C-17 Nacelle will show, learning across organizational boundaries is difficult. Most organizations do not do it well, even when the organizational boundaries lie within the same building. An integral process

should therefore give some pause to the make-buy decision maker. If one or more organizational boundaries cut through an integral process, the ability of a company to learn could be greatly hurt. To minimize this risk in such situations, a well-managed communications infrastructure and well trained personnel are needed.

10.2.7. Human Content of Work

The concept of the Process Interactions Matrix can be extended further, to include more detailed information about the way in which the process works. Of particular interest here is the use of the PIM to capture information about the amount of human content in the process.

It has been noted several times in this thesis that learning occurs through feedback. A point that was implicit in that discussion is that, for feedback to be useful, it has to be processed, understood and acted upon. In terms of modern technology, this means that humans must be involved in the feedback processes. They must either be directly involved through manual labor, or indirectly involved through the reading and analysis of data on a computer screen or print-out.

The interactions that are documented in the basic PIM do not provide a complete description of feedback opportunities. To gain the complete picture, the interactions must be differentiated. There are four dominant forms of interactions in manufacturing systems:

Worker-to-Worker (or Organization-to-Organization): This type of interaction occurs whenever two organizations interact directly. Examples of this might be transportation of parts from one location and group to the another, or the interaction of a maintenance team with a production team.

I. **Part-to-Part**: These interactions occur whenever one part directly affects another. They are almost always accompanied by a part-tooling or part-worker interaction. Tolerance propagation and parts which are located using features on other parts are examples of part-to-part interactions.

II. **Part-to-Tooling:** Interactions of this nature occur when the location or shape of a part is directly affected by the action of some tool, whether a cutting tool or an assembly fixture. An example of a part-tooling interaction might be a case where a part is located on a fixture using surface locators.

III. **Part-to-Worker:** This interactions class refers to cases in which a worker directly alters some feature of a part, or in which worker judgement and decisions greatly affect the shape or location of a part. The assembly of flexible parts, where parts must be bent and aligned by a worker, is an example of this interaction.

Each type of interaction has different degrees of learning associated with it. In general, the amount of learning is determined by the level of human content of work. A guide to this level can be obtained by considering two factors: error absorption and planning. The latter refers to the amount of systems knowledge and proactive activity necessary for a given interaction to occur successfully. For example, in some cases, rivets must be inserted in a particular direction or order for all of the rivets to be successfully inserted. The former, error absorption, refers to the ways in which deviations from the desired state are brought to light. In some cases, it is obvious to a worker on the process that an error has occurred. This might occur when, for example, two parts fail to snap together as they had been designed to do. In other cases, errors are absorbed by other elements of the system, and are not noticed at the time by the workers. Such a case might occur when a part is added to a system by placing it in a fixed location on an assembly jig.

In considering both the location and planning issues, it is useful to ask the question "How can the step fail?" Consideration of these failure mechanisms often highlights the critical factors at play.

Based on these ideas, some general rules of thumb can be generated to approach the question of learning in a manufacturing system:

- **Worker-Worker:** Highly dependent on the exact tasks. No rule.
- **Part-Part:** There are two types of part-part interaction - those accompanied by part-worker interactions and those accompanied by part-tooling interactions. When the part-part interaction is accompanied by a part-worker, the general level of learning is **high**. When it is accompanied by a part-tooling interaction, as in robotic assembly, the level of learning is **low**.
- **Part - Worker:** The learning in this case is **high** because the interactions occur directly as a result of a workers actions and decisions.
- **Part - Tooling:** Here, the level of learning is generally quite **low**, because the tool often does much of the work in locating and `planning'. However, the exact level of learning does obviously vary depending upon the type of tool. Robotic assembly is much different from assembly using a fixture. The latter is often accompanied by a small degree of part-worker interaction.

As noted, few of these interactions occur in isolation. However, to avoid unnecessary confusion, only the interactions that greatly affect the outcome of a task should be considered. Part-part and part-tooling interactions must always be evaluated with any accompanying interactions in mind.

Using these rules of thumb to code the PIM, a rough learning map is obtained. Regions of high learning potential can be identified, and infrastructure building activities focused there.

10.3. The Need for Precision Assembly

The aircraft industry is a low volume, high fixed cost industry. Typical production rates for commercial aircraft range from about 3-6 per month. Parts for these aircraft are produced in various places around the world. They are assembled into subassemblies at still other locations, and are shipped to a final assembly plant where the aircraft is assembled.

Much of the assembly work is still a largely manual process. This is true in both military and commercial production. Large, inflexible fixtures are used to locate and assemble parts. Teams work around these fixtures, using them as guides and locators. Much of the work, however, is done directly by the workers in the team.

These fixtures are both large and costly. They take up valuable floor space, resulting in larger facilities, overhead and often inventory costs.[1] In addition, they cost several hundred thousand dollars, depending on their size and complexity, and are very inflexible. Only one assembly design can be produced on these fixtures, often only in a particular assembly sequence. If demand for one type of aircraft is low but that for another is high, the fixture for the former might become underutilized at the same time as there is a shortage of fixtures to meet demand for the latter.

Eliminating fixtures would solve many of these problems. A flexible assembly process that did not rely on fixtures would result in lower capital costs and greater product and capacity flexibility. It would also allow the assembly work to be conducted in smaller facilities.

Precision Assembly is the name given to a set of fixtureless assembly processes being developed by several aircraft manufacturers. For this case study, a fixtureless assembly process for the horizontal stabilizer of a large aircraft was studied. Although the case was studied in detail during extended on-site plant visits, the details on the Precision Assembly process presented in this section are based upon a process developed by members of the MIT Fast and Flexible Manufacturing Program. This work is described in [7].

10.3.1. Implementation Issues

Precision Assembly represents a radical change from current assembly practices in the aerospace industry. From a technical perspective, the way in which assembly occurs will be fundamentally different. Instead of locating parts using fixtures and techniques such as match drilling (where two parts are lined up and a hole drilled through them), parts will be located using

features established during the fabrication stage. Issues surrounding tolerance propagation and temperature control are more important as the process is less forgiving of errors and variation.

The absence of fixtures and the reliance on part features in the assembly process also has large implications for the organization. Workers will need a different set of skills and roles to operate the new system. Supplier roles will also change, as must the importance of timely information flows. Learning rates will be affected, as will the ways in which learning is accomplished.

All of these organizational and technical issues must be addressed in order for Precision Assembly to work. Failure to address these issues will result in poor overall performance, long start-up times and high error rates. In order for Precision Assembly to be a success, it is vital that efforts be made to change both the technology and the organization. Much work is happening on the former front; very little on the latter.

In this chapter, some of the organizational issues involved in Precision Assembly are examined to discover exactly what should change when implementation occurs.

10.3.2. Horizontal Stabilizer Skin Panel Assembly

Before any of the issues surrounding the existing (as-is) or the Precision Assembly processes are discussed, the parts and assemblies must first be described.

The horizontal stabilizer is the wing-like structure found on the rear of most aircraft. The skin panel assemblies make up the top and bottom of the box-like stabilizer structures. Rib structure are used between the panels to help form the shape and to provide some stiffness.

The skin panel assemblies are made from thin sheets of aluminum. There are two parts to each skin panel: the aft skin and the forward skin. The stiffness of these sheets is increased by attaching long slender beams, called stringers, to the skin so that each stringer runs along the length of the skin, from the inboard to the outboard end, as shown in Figure 10-3. The forward and aft skins are joined together by Stringer 3. Finally, at the inboard end of the assembly is a structure known as a plus chord. This structure bears much of the load that is seen by the cantilevered stabilizer.

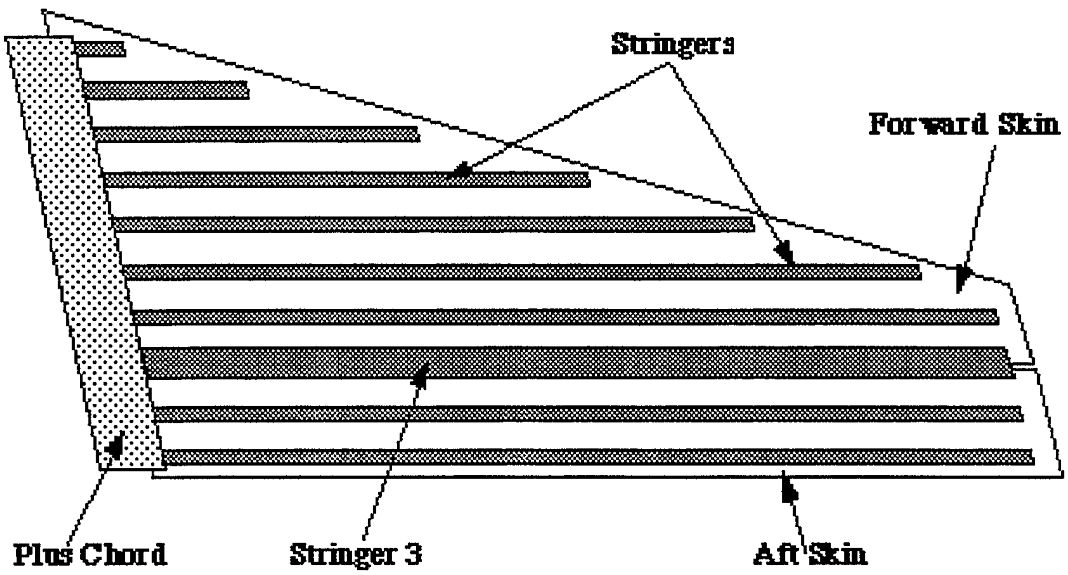


Figure 10-3. Schematic of a horizontal stabilizer skin panel assembly.

At present, the horizontal stabilizer skin panel is assembled by a team of three people. Several hand tools, as well as a fixture, are used. In the proposed Precision Assembly Process, a flexible contour fixture is used to hold the skins in the proper shape. Holes and slots are the primary features used for part location. These features are established at the fabrication stage. The assembly sequences for the as-is and proposed processes are found on the Process Interactions Matrices, Figure 10-4 and Figure 10-5.[2]

10.3.3. Key Characteristics

The first step in analyzing the two processes is to understand their goal. That is, the Key Characteristics for the system must be understood. As both processes produce the same product, the KC's for both processes are the same. As identified by Cunningham et. al. [7], there are five KC's:

- PKC: Gap between the forward and aft skins of the skin assembly.
- AKC #1: Plus chord angle relative to aft skin edge.
- AKC #2: Plus Chord fore/aft position relative to aft skin.
- AKC #3: Spacing and contour of the splice plate, skin, plus chord sandwich structure.
- AKC #4: Blade seal hole locations. Once the KC's for the processes have been identified, detailed analysis and comparisons can be completed.

10.3.4. As-Is Process

As in the nacelle example in Chapter 5, the first step in analyzing any process is to understand the general assembly map. Several groups contribute to the as-is assembly process. There are basically four separate parts suppliers (all of them different organizations within the in-house fabrication department) and an assembly organization. Each of the four suppliers is responsible for making their parts (the skins, plus chord, splice plate and stringers) and shipping them to the assembly station. At the assembly station, the skin panel is assembled using one fixture and several hand tools. Once the assembly is completed, it is sent to another group for riveting. It is then incorporated into the overall stabilizer structure.

Communication between each of these five groups tends to be limited to structured channels, such as IPTs and vertical management structures. Improvement efforts have a local, team-oriented focus. Information does not flow between teams on a regular basis. Instead, information is passed on to another group only if a problem is seen with the parts that group is producing.

Once the general assembly map is understood, a detailed examination of the interactions within the system can be undertaken. For the as-is process, this can be done in two ways. First, interviews of the personnel currently working on the process can be performed. Second, walking through the operations and understanding all of the factors that can cause variation in a KC can illuminate several of the interactions.

The reader will note that what these two steps are similar to those used to document the physical chain in the previous case study. In essence, that is precisely what we are doing here. However, because the nature of this study is different, additional techniques are needed. In particular, because one of the objectives of this case is to understand the total organizational impact of the new process, greater effort must be spent on understanding these organizational issues.

The next step is therefore to break down the interactions into different categories. As noted in Chapter 4, there are four types of possible interactions. In order to differentiate the interactions into these four groups, each interaction must be examined closely. For example, when a stringer is first introduced into the assembly station, there is an interaction. This interaction exists because the stringer must be transported from the machine shop to the assembly area. It is therefore a worker-worker interaction.

As a further example, consider the process of locating the plus chord on the fixture. In this case, two interactions were noted. First, there was an interaction with the bump-forming process, where the plus chord obtains the shape with which it enters the assembly area. This is a part-part interaction, as

the plus chord locating process depends upon the part features formed at the bump form stage. Second, there is worker-worker interaction associated with transporting the plus chord from fabrication to assembly.

Finally, consider the step at which the aft skin is clamped to the stringers on the fixture. Here there is one interaction, with the step at which the stringers are themselves loaded and clamped to contour. This interaction is different from those previously discussed, however, in that two types of interaction are happening at once. There is a part-tooling interaction, as the skin is being clamped into position using features on the fixture. In addition, there is a part-worker interaction, because the worker has a considerable role in deciding how to clamp the skin. Some judgement and experience is required in order for the step to be performed correctly.

Using this detailed knowledge of the interactions, a PIM for the as-is process can be drawn. The PIM is shown in Figure 10-4. Figure 10-6 shows the key for the interactions. The numbers in the first row and column in the matrix refer to process steps. A brief description of these steps can be found in Table 10-1. Note that the thick line that runs across to the diagonal represents an organizational boundary (Fabrication and Assembly organizations).[3]

It is worth noting that the PIM is used here because it conveys information that cannot be conveyed using a contact chain. In Figure 10-4, worker-worker interactions (`service elements') and part-worker interactions are shown. Displaying these interactions on a contact chain would be extremely difficult. Only part-part, part-tooling, and some worker-worker interactions (`physical elements') can easily be shown on a contact chain.

A quick examination of this PIM gives considerable insight into the nature of the as-is process. First, note that the PIM is broken down into several sections, each representing a different type of coupling.[4] Most of the interactions are located in the Assembly coupling and Fabrication-Assembly coupling regions. When only the physical elements are considered (i.e,. the worker-worker interactions, which mostly represent transportation, are ignored), the Assembly region is by far the most integral of the three regions.

Second, virtually all of the interactions are contained within a single team. The only exception are the part-part interactions associated with the plus chord and splice plate assembly steps. In addition, the majority of the interactions contain a combination of part-tooling and part-worker interactions.

Using this quick analysis, one can make several conclusions about the nature of the as-is process. First, the power to solve problems associated with the five KCs lies almost entirely with the assembly team. This is seen by the fact that the majority of the interactions in the system occur within the

boundaries of the assembly team. Fabrication and assembly are, for the most part, modular processes.

A follow-on from this is that the majority of learning in the as-is system happens primarily through either implicit loops or team-based explicit loops. Therefore, micro-skills are particularly important in the as-is process. In addition, the roles of the work teams, which enable them to effectively encompass all of the learning loops, are well designed from a learning perspective.

However, that said, the other point that should be made about the as-is process is that the limited number of learning loops does not allow for many learning opportunities. While the low-level of complexity in both the organization and technology is beneficial from a learning perspective, some complexity can easily be managed and incorporated into the system. For a small amount of added complexity, large amounts of learning can likely be achieved.

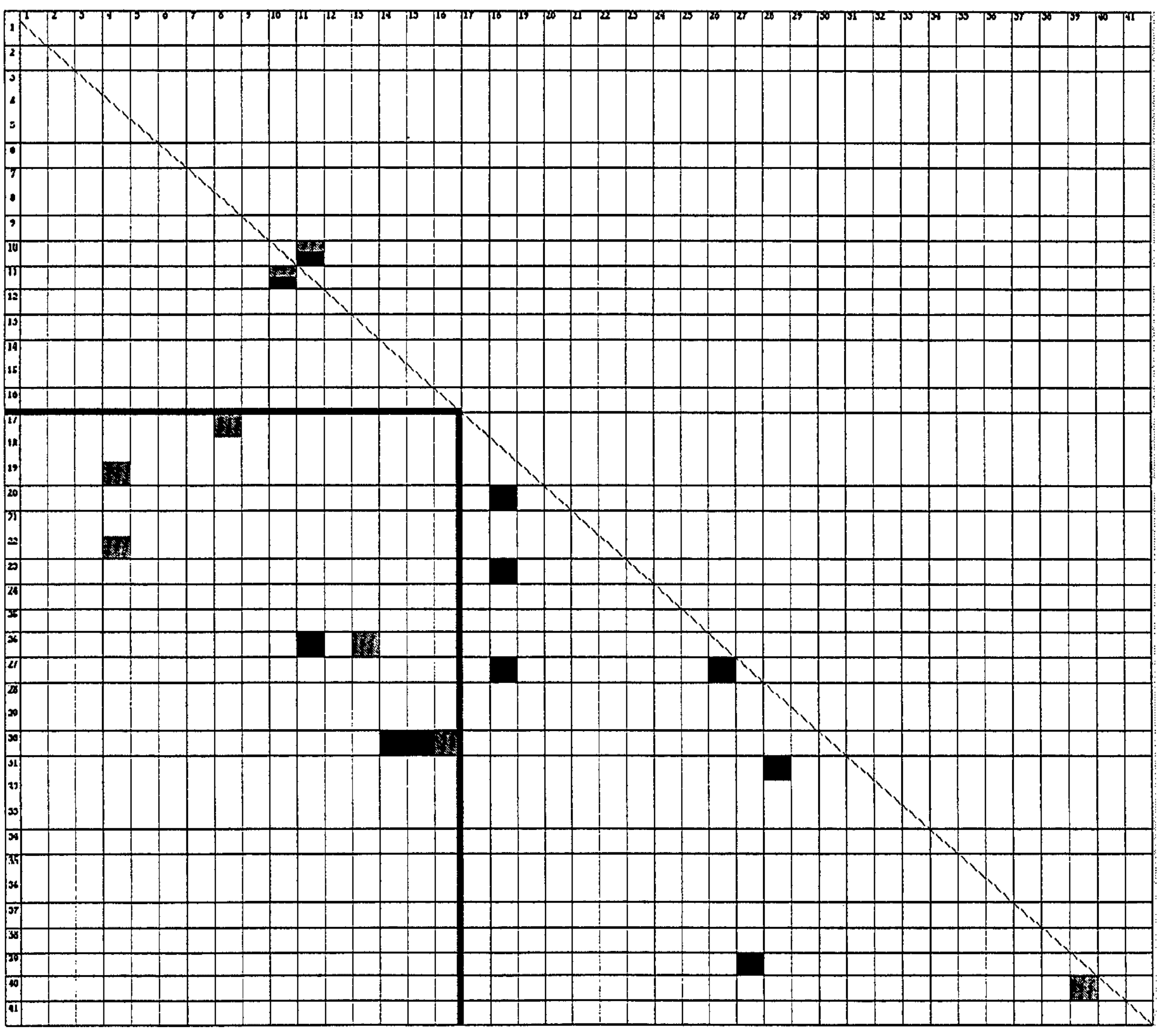


Figure 10-4. As-Is Process Interaction Matrix

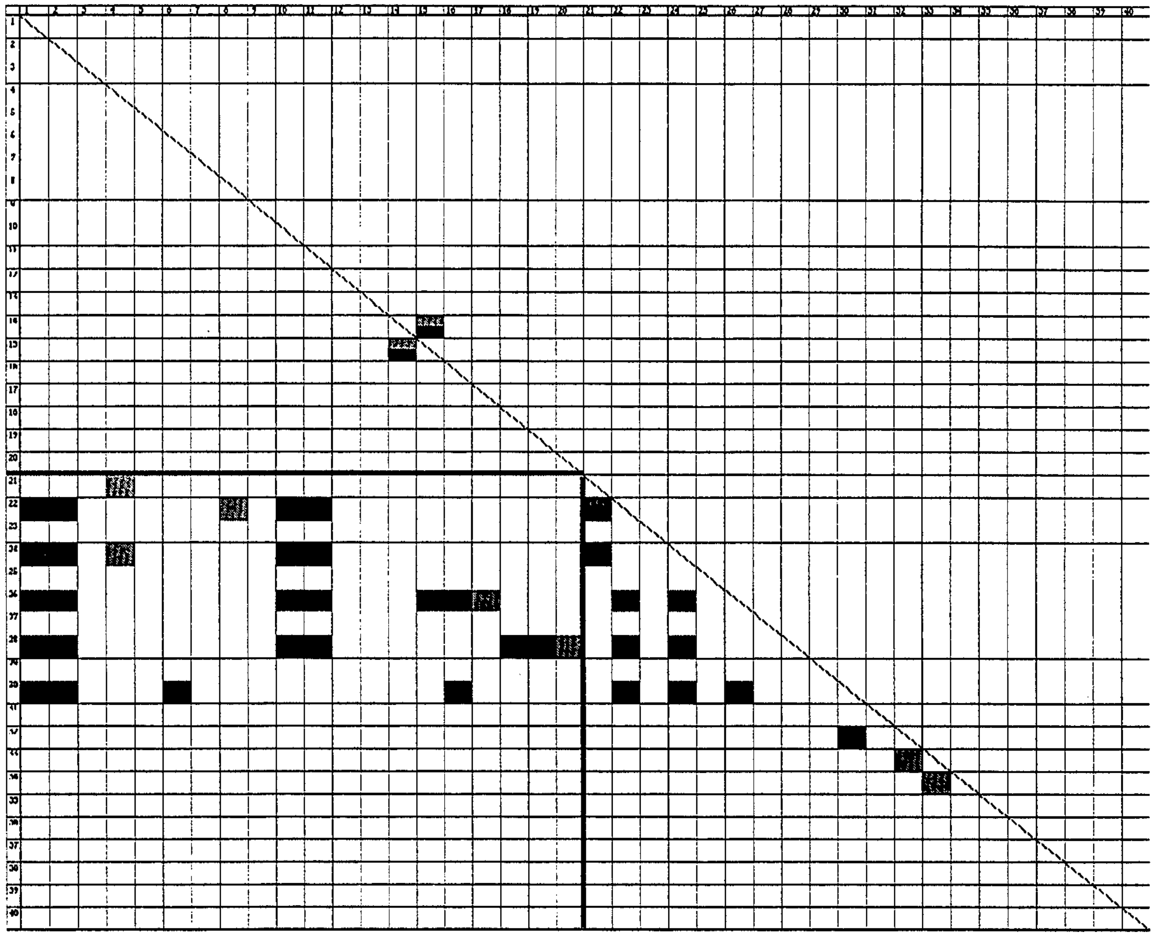


Figure 10-5. Proposed Process Interaction Matrix

10.3.5. Precision Assembly Process

Much about the operating environment remains the same in the proposed, Precision Assembly process and in the as-is process. The assembly map is likely to remain constant, with four suppliers and one assembly team. What will change, however, is the roles of each of these organizations.

To understand exactly how their roles will change, the PIM analysis that was carried out for the as-is process must be repeated for the proposed process. One critical difference between the two processes must be kept in mind when constructing the PIM. Unlike the as-is process, the proposed process has not yet been implemented. This means that the techniques used to construct the PIM in the as-is case must be modified.

Instead of using interviews and observations, imagination and detailed analysis of the proposed assembly steps must be used. One must imagine the process in action, and walk through it in one's mind, asking the same questions as in the as-is case. How can variation enter the system and affect

the KC? What parts and tools interact with each other? How exactly does this process work? How can it fail?

The implications of using this technique is that it is extremely likely that the PIM will be wrong. However, the challenge is in being close enough at an early stage to get a general idea of the preparation needed for implementation. The actual details can be understood as the process gets closer to implementation, or even after implementation has occurred. It will take some time before the PIM becomes fairly static.

Many of the interactions in the proposed process come from the fact that features created in one organization determine the performance of the system in another organization. Consider, for example, the step where Stringer 3 is located and attached to the aft skin. In the as-is process, this was accomplished using tool features and some worker judgement. The stringer was match drilled to ensure that the parts fit together. The match drilling process absorbed much of the variation.

In the proposed process, however, this is not possible. Holes and slots are created in both the aft skin and in Stringer 3 during their fabrication. This creates part-part interactions between the step when the assembly occurs and the steps where the holes are created. In addition, the step where the aft skin is located is itself important. Variation in any of these steps can prevent the assembly step from being successful. For example, if the holes are fabricated in the wrong places, they will not line up, and the fastener cannot be inserted.

Because of the widespread use of fabricated features, many of the interactions in the system are similar to that described above. The end result is shown in Figure 10-5. The description of the process steps in the PIM can be found in Table 10-2.

Again, several conclusions can be drawn from an examination of the PIM. The process is, in general, more integral than the as-is process. There is a great deal of both Assembly and Fabrication-Assembly coupling. Furthermore, most of the interactions are part-part interactions with only small amounts of part-worker interactions.

The presence of Fabrication-Assembly coupling indicates that there are explicit loops which transcend organizational boundaries. The fact that Assembly coupling also exists means that some of the loops are contained within the team. This combination represents a much more complex situation than that which existed in the as-is case.

Because of the increased organizational complexity associated with the explicit loops, techniques for reducing the effective complexity must be put into place. At least three different techniques can be used. First, the interactions map represented in the PIM shows the communications

channels that need to exist. Effort should be made ensuring that these channels are in fact created - the perceived chain should match the physical chain. One way to do this would be to use computerized information management systems to make information transfer more efficient. Second, some of the organizational boundaries can be made more transparent. For example, teams could visit each other on a regular basis to learn about other processes in the system that affect their process. This would allow workers to gain a greater overall understanding of the workings of different elements of the system. Lastly, worker roles and skills can be designed so that workers are comfortable and able to work in the integral environment. They need to be given a mix of macro and micro-skills, and roles that allow both team-based system-wide improvement activities.

An important point to notice at this point is that these conclusions would remain the same even if a few of the interactions on the PIM are incorrect, or if some are left out. While the PIM should be updated as more accurate information becomes available, useful information can still be obtained from the PIM even at early stages in the process development, when all the details are not yet known.

10.3.6. Comparing the As-is and Proposed Processes

There are clearly some striking differences between the as-is and proposed processes. First, consider process architecture. The proposed process is has a much more integral architecture than the existing process. This makes sense intuitively. In the as-is case, a great deal of the part location was handled by tools and fixtures. Part locations were not a function of any previous steps. However, in the fixtureless case, part features, which were created during earlier fabrication stages, are much more important to the overall outcome. Thus, the amount of Assembly-Fabrication interaction is much greater in the proposed case.

Second, the nature of the interactions is different in the two cases. Because of the use of fabricated locating features, much more part-part interaction exists in the proposed case. This part-part interaction naturally has a great deal of part-worker content, because it is the worker who must line up the features and connect the two parts. (Note that in some cases, part-part may be accompanied instead by part-tooling interactions, as in a robotic assembly station.) The as-is process, on the other hand, has a great deal of part-tooling interaction. (Again, part-tooling interaction can either be accompanied by part-worker interactions, as in this case, or be completely part-tooling, as in robotic assembly.)

10.3.7. Learning and Worker Management in Precision Assembly

The two insights gained through use of the PIM provide valuable information about the changing nature of the assembly process, and have great implications for organizational design and operation. In particular, the two areas in which the implications are the largest are in learning and workforce management.

In the as-is process, the ratio of interactions to distinct assembly steps is quite low when compared to the proposed process. This means that the majority of learning that occurs in the as-is process will be implicit learning. There is some limited opportunity for explicit learning within the assembly team. However, because of the nature of the interactions, this explicit learning will not greatly improve the learning rate. Part-tooling interactions, even when accompanied by part-worker interactions, provide limited feedback to the worker. Much of the feedback is instead absorbed by the tool. In this case, the fixtures absorb much of the variation and interactions, often leaving the worker with simple pick and place tasks.

Opportunities for implicit learning also exist within the proposed process. Because the amount of human content involved in the tasks in both processes remains about constant, the amount of implicit learning should remain about the same. However, the high number of powerful explicit loops makes this type of learning a much greater factor. The part-part interactions provide much more feedback directly to the worker. In this case, the parts are somewhat flexible, meaning that some variation could possibly be absorbed by worker `fixes'. However, the majority of the problems will come to light much more quickly than in the as-is case, meaning faster feedback and higher learning.

None of the learning improvements will occur unless the explicit loops are nurtured. In the simple case in which they are ignored, no explicit learning will happen. In fact, one of the risks of explicit loops is that neglect will lead to an overall worsening of the learning rate, with subsequent cost and quality problems. So, the risks are much higher with the integral architecture. However, if properly designed and implemented, the explicit loops can be a source of great gain.

One of the factors involved in creating the explicit loops is training the workforce to operate in this new environment. Workforce management techniques and philosophies must not remain as they are in the as-is process. Without innovation in the management of the workforce, the feedback channels necessary for information to flow up and down the chain will collapse.

The fundamental change that will occur when Precision Assembly is implemented is that **direct workers will become a much more critical part of the overall process**. Their responsibilities will increase, as will their contribution to the system. This is a direct result of the integral nature of the Precision Assembly Process. Workers will have to manage, understand and use the interactions in the process.

Consider just one of the integral regions - where the plus chord is attached to the system (Steps 26 and 27) - as an example. The PIM in Figure 10-5 indicates that there are several interactions that are important at Step 26, where the plus chord is located to the skins and stringer 3. These interactions fall within both the Fabrication-Assembly coupling and Assembly coupling regions, and are a combination of part-part and worker-worker interactions. In addition, note that the parts being used in Step 26 are a combination of fairly rigid (plus chord) and flexible (skins and stringer). First, consider the interactions in the Assembly coupling region. These are the interactions which the worker has direct control over. The explicit loop is contained within the team, and organizational complexity is relatively small. However, because of the flexible nature of some of the parts, the part-part interactions in this region rely on the workers' actions and judgements. It is possible that part could be forced to fit, perhaps inadvertently. The direct workers are the only ones who can manage or plan the interactions and ensure that problems are noticed and corrected. In contrast, in the as-is process, the tools and fixtures largely take care of these `management' and planning tasks. Much of the variation is absorbed by the fixtures, and many of the problems are, in fact, hidden by the fixtures. In the as-is process, the fixture was the glue that held the process together; in the Precision Assembly process, the people are the glue.

Second, consider the part-part interactions that lie in the Fabrication-Assembly coupling region. Here, the interactions exist because of features that were made in parts at the fabrication stage. There are at least two possible ways to manage these interactions. On the one hand, the direct workers could be responsible for their management, meaning that they would be the ones who would communicate with the fabrication teams. In this scenario, the direct workers obviously need a great deal of system knowledge to ensure that their perceived chain is accurate, and to aid in troubleshooting. On the other hand, indirect workers could be made responsible for all inter-organizational communication. However, as pointed out in the nacelle example, this leads to several problems. Foremost among these is the delay in the feedback loop that results from the addition of the extra element (indirect workers) into the loop. A related problem is that the group responsible for the problem recognition (direct workers) is not the same as the group with problem solving responsibilities (indirect workers). Explicit-loop learning is therefore much less efficient. The ideal scenario is, therefore, the former. Indeed, this scenario is much more in line with the conclusions reached by examining the

Assembly coupling region interactions. As a result, it can be concluded that not only is it more efficient for direct workers to assume a much larger role in the new process, it is, in fact, necessary for the system to operate smoothly.

The above example focused on only two steps in the Precision Assembly process. Yet, those steps are typical of many of the steps in the process. Given this situation, the issues identified in the above example are greatly magnified. However, the example should not lead anyone to think that indirect workers will no longer have a place in the assembly process. On the contrary, they should be involved, but working as a resource and aid for the direct work teams, instead of as an independent entity. They can become a source of new ideas, technical expertise, and systems knowledge, while leaving much of the actual analysis and the main tasks (such as communication) associated with both local and systems level problem solving to the direct teams.

To prepare for this change, the direct and indirect workers must be involved in the actual design of the process, and in the creation and operation of the organizational structure. A situation in which a group of engineers design a process and then try to implement it will lead to reduced buy-in and motivation for the new process by the direct workers. If this lack of buy-in occurs, it will foster a positive feedback loop where the effectiveness of the new process is continually reduced; the process will enter a death spiral from which it will be very difficult to recover.

Among the changes needed in the workforce are improved systems thinking and communications skills. Team structures should be created to encompass as much of the explicit loops as possible. This could be accomplished by, for example, creating a liaison team in areas in which there are large clusters of interactions. These teams would be made up of direct and indirect workers from the teams responsible for and affected by the interactions. It is critical to have both the direct and indirect workers (maintenance, transportation, engineering support as well as mechanics) involved in the process because each of these people does some of the learning and possesses some of the knowledge the others need.

With all of the changes needed in the areas of workforce management and organizational design/supplier management, it should be clear that these issues must be addressed before implementation occurs. This is particularly important because of the increased complexity in the proposed process. While explicit loops provide greater opportunities for learning, operating the system without actively taking steps to reduce the complexity will yield a chaotic and worsening situation. Only by taking proactive complexity management steps can a disastrous situation be avoided.

Worker - Worker
Part - Part
Part - Tooling
Part - Worker

Figure 10-6. Key for Process Interactions Matrices Interactions

Step Number in PIM	Description
1	Machine on Gantry Mill
2	Shot Peen
3	Paint
4	Anodize
5	Machine undersize on spar mill
6	Shot Peen
7	Drill undersized holes
8	Paint
9	Machine
10	Inspect on Check Fixture
11	Bump form on arbor press
12	Shot Peen
13	Paint
14	Machine and drill on Gantry Mill

15	Shot Peen
16	Paint
17	Locate stringers
18	Clamp to contour
19	Locate aft skin
20	Clamp to stringers
21	Match drill and tack
22	Locate forward skin
23	Clamp to stringers
24	Match drill and tack
25	Spray dots on skin
26	Locate plus chord
27	Match stringers to plus chord
28	Drill holes through skin and plus chord
29	Trim forward skin
30	Locate splice plate using coord holes
31	Drill holes
32	Locate splice plate in main fixture

33	Drill holes
34	Disassemble plus chord and splice plate
35	Deburr
36	Reassemble
37	Fasten
38	Remove assembly from fixture
39	Shim stringer and plus chord
40	Fasten stringers 3-11to plus chord
41	Rivet skins to stringer (not Aft skin to S3)

Table 10-1. As-is Process Fabrication and Assembly Steps for PIM in Figure 10-4

Step Number in PIM	Description
1	Machine Skins on Gantry Mill, including features
2	Shot Peen
3	Paint
4	Anodize
5	Machine Stringer 3 undersize on spar mill
6	Drill holes
7	Shot Peen

8	Paint
9	Machine remaining stringers undersize on spar mill
10	Create features on mill
11	Shot Peen
12	Paint
13	Machine plus chord and create features
14	Inspect on Check Fixtures
15	Bump on Arbor Press
16	Shot Peen
17	Paint
18	Machine splice plate and create features on gantry mill
19	Shot Peen
20	Paint
21	Load Aft Skin on Flexible Contour Fixture
22	Locate Stringer 3 to aft skin holes and slots
23	Tack Stringer 3 to aft skin
24	Locate forward skin to Stringer 3 holes and slots
25	Tack Forward Skin to Stringer 3

26	Locate Plus Chord to aft and forward skin and S3
27	Tack Plus Chord to parts
28	Locate Splice Plate to aft and forward skin and S3
29	Tack Splice Plate to parts
30	Locate stringers to plus-chord and skins
31	Tack stringer to +-chord and skin
32	Shim stringers to +-chord
33	Autorivet
34	Drill through splice plate, +-chord and skin
35	Drill blade seal holes
36	Drill stringer to +-chord holes
37	Disassemble
38	Deburr
39	Reassemble
40	Fasten

Table 10-2 Proposed Process Fabrication and Assembly Steps

[1]Although large facilities are not always accompanied by large inventories, the discipline imposed by the lack of space in a small facility ensures that inventory levels are maintained at a lower level. Based on a lecture at MIT (11/96) by Mr. David Fitzpatrick, Senior Manager for Strategic Planning, The Boeing Company.

[2] The proposed Precision Assembly process was developed by Messrs. Timothy Cunningham and Krish Mantripragada, and Dr. Daniel Whitney, of the MIT Fast and

Flexible Manufacturing Process. Details of the development process and of the assembly steps can be found in [7] .

[3]Please refer to Figure 4.6 for further discussion of this point.

[4]Please refer to Figure 4.6 on page 72 for a discussion of the difference between coupling regions and interactions.

10.4. Conclusions

10.4.1. Aligning Technical and Organizational Strategies

Learning rates are typically considered to be intrinsic properties of systems. Because of this, little thought goes into "design for learning". Yet, in industries in which learning is extremely important (those with short product life cycles or low production volumes), the success of a new product or process can be greatly improved when learning is considered as a process is being designed.

Only recently have studies begun to examine the mechanisms behind learning in product development and manufacturing systems. Several authors spell out the role of organizational factors in the success of new product and process implementation. Few of these authors provide tools for understanding exactly how to analyze and make decisions on the necessary organizational adaptation.

This thesis represents an initial attempt at developing a framework for understanding the organizational adaptation necessary when a new process is introduced. This chapter contains a summary of the conclusions reached in the thesis, as well as a discussion of some of the implications of these conclusions.

10.4.2. Two Categories of Learning

All learning occurs through feedback. One of the central hypotheses of this thesis is that there are two fundamental feedback mechanisms behind the `learning by doing' phenomenon that is the basis of the learning curve. Implicit loop learning is that which happens at the individual worker level as a `natural' part of their tasks. Explicit loop learning is that which happens through deliberate actions and effort. Both of these loops operate in both the single-loop and double-loop learning environments defined by Argyris. [2]

The concepts of implicit and explicit loop learning help form a link between two areas that have, until now, been quite separate: process improvement and learning. Process improvement efforts such as those developed by Dr. Deming involve the creation of explicit learning loops. The

learning-through-experience phenomenon, on the other hand, acts primarily through implicit learning loops.

Furthermore, implicit and explicit learning loops provide the link between organizational and technical aspects of manufacturing systems. Combined with tools such as contact chains and the Process Interactions Matrix, a reliable map of the organizational infrastructure needed for successful process implementation can be generated. Communications flows, skill levels and worker roles can all be designed before a process is implemented.

Lastly, the concepts of implicit and explicit learning loops helps to explain one of the misconceptions behind the learning curve discussions - that labor-intensive processes must learn faster than capital-intensive processes. This holds for the most part when only implicit learning loops exists. As implicit learning loops are contained completely within a single person, the more people contribute to a process, the more learning will happen. However, explicit loops are not subject to this constraint. Their only requirement is that there be a person at at least one link in the loop. The rest of the links could involve machines. Neither implicit loops nor explicit loops are stronger than the other. In some cases, labor-intensive processes might have higher learning rates than similar, capital intensive machines. The important point is that this need not always be the case.

The main contribution of this thesis lies in the links made between process improvement and learning on the one hand, and between learning and technical systems on the other.

10.4.3. Design for Learning

Whether one is dealing with a new process that has yet to be implemented, or with an existing process that is not operating at its peak level, certain techniques developed in this thesis can help to improve a system's operations.

The primary method for improving systems is to identify discrepancies between the desired state of the system, and the actual state. This is done using physical and perceived chains, illustrated using either the contact chain or the process interactions matrix. The physical chain represents the communication that needs to exist for a system to perform successfully. As such, it also represents the explicit learning loops that need to be created. Matching this desired state to the actual state, as shown by the perceived chain, allows resources to be allocated correctly and feedback to be efficiently processed and utilized.

Once learning loops have been identified and created, they should be strengthened so that the maximum benefit can be realized. Depending on the

type of loop, loop strength depends on a variety of factors including worker roles and skills, the efficiency of feedback channels and the complexity of the organizational and technical systems compared to the worker skills and roles. Techniques for decreasing the complexity of systems (thereby improving learning rates) include the use of IT systems to facilitate information flows, and the design of worker roles to encompass all of the explicit loops. To this end, a general rule of thumb is that processes contained within a team should be as integral as possible, whereas the processes between teams should be as modular as possible. There should be as few interactions between teams as possible. The limiting factor in either case is the manageable level of complexity.

10.4.4. Continuous Process Improvement

Continuous process improvement methodologies have been extremely successful in increasing the quality and reducing the cost of products. The traditional techniques - risk analysis, SPC, cause and effect diagrams - have their limitations, particularly in integral process environments.

One of Deming's 14 Points for Top Management [8] states the importance of requiring statistical evidence of part quality from critical part suppliers. This is certainly critical. However, a negative result has been the promotion of a part-focus, often at the exclusion of all else. In many products today, it is not so much any particular part that is important as much as it is the way in which these parts come together. The critical interfaces and process flows are as important as the critical parts.

In systems with many interconnections in either the product or process, these interfaces and flows are often the most significant sources of variation. Using traditional improvement techniques, however, these sources are often passed over. The contact chain is a tool for refocusing process improvement efforts. Parts and interfaces that form part of a particular contact chain are the sources of variation for a system.

The advantage of the contact chain approach is that the biases developed through experience and ingrained philosophies do not play a role. Techniques such as risk analysis, by contrast, are often tainted by the lack of systems knowledge of the workers, or by internal biases. Using the physical contact chain as a focus for SPC, root cause analysis and other improvement techniques allows the part and process focus to be combined into an overall systems view.

10.4.5. Agility, Virtual Organizations and Supply Chain Management

Using the systems view provided by the contact chain results in more complete process improvement efforts. However, the implications of this approach are far-reaching.

Consider the discussions of agile production and virtual organizations. In such environments, suppliers are changed as needed, partnerships are made one day and dissolved the next. In an increasingly `agile' environment, in which suppliers and products both change rapidly, there is even less opportunity to understand other processes, not to mention your own processes.

How much process improvement and learning can occur in this environment is questionable. This seems to be a major limitation of the agile model, and one which could significantly degrade its effectiveness, particularly in environments with integral process architectures. As the process architecture becomes more modular, the possibility of successfully manufacturing in an agile environment improves.

10.4.6. Make-Buy Decisions

Fine and Whitney [12] have discussed the link between product architecture and make-buy decisions. Much of this discussion relies on the level of product and process knowledge possessed by the product company. The more critical the part to the overall function of the product, and the more reliant you are on the supplier for knowledge and expertise, the riskier is outsourcing.

Process Architecture as another indication of outsourcing risk. The risk here is not that the supplier could supplant you; instead, it is that outsourcing will significantly affect productivity and quality in your process. Integral processes rely heavily upon other stages being completed successfully. When a supplier has control of critical stages in the KC realization chain, the control you have over the process outcome is greatly diminished.

More importantly, however, as links in the chain are outsourced, the less systems knowledge is held by the prime. This affects the ability of the prime to improve their processes and products, and their capability for developing new processes that overcome the limitations of the existing ones.

The issue here is one of knowledge management. If two companies have equally integral processes, dispersed to the same types of supplier organizations, the one that can manage the system knowledge will have the competitive edge. Knowledge management should be a core competency of any company making a product in a complex product realization web.

10.4.7. Reengineering

The fundamental shift in outlook from parts to processes and systems is, of course, not new. One of the places where it can be seen is in the business process reengineering efforts that are taking place in corporations throughout the world.

The initial idea behind reengineering was that, by reorganizing businesses to focus upon the processes that produced their products rather than upon functional organizations, productivity and quality could be improved.

Much of this is similar to the idea behind the contact chain. In a manufacturing system, most of the emphasis is on the functional organizations or individual assembly stations and parts. Changing this to a focus on the processes through which the outcomes (KCs) are achieved will yield gains in productivity, time and quality.

Both approaches emphasize the power of designing the process specifically to achieve the desired outcome. Instead of accepting the chains that have built up over a long period of time, one should proactively create the chains that are best for the system.

A few differences do exist. First, most manufacturing systems cannot be reorganized very easily. The change to a process focus happens more on an organizational level than on a fundamental structural level. Second, reengineering is process focused, but not systems focused. Similar to the initial `tree' view of the supply chain, reengineeding efforts typically do not account for interconnections and feedback between elements. Contact chains can add to reengineering by incorporating the systems view into standard reengineering efforts.

Another difference between reengineering and the work presented in this thesis is that the standard reengineering approach is to make processes as simple as possible. While this sounds appealing, it may not always yield the best results. From the perspective of learning, higher levels of learning should be possible if one is willing to live with some complexity. The challenge is not in simplifying processes as much as possible, but in recognizing the level of complexity that can be effectively managed.

10.5. References

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11. Case Study[39]

11.1. Introduction

This section of the report describes a method of designing flexible and low-cost assembly systems for large sheet metal structures, such as automotive bodies and aircraft airframes, to replace rigid lines previously made-up of dedicated, inflexible fixtures. The application for the method is to reproduce the assembly dimensions and tolerances without fixtures, as well as support the parts against gravity, without committing to any single use equipment and to do so in an economical manner. Our method supports system-level assembly planning early in the planning process, allowing candidate assembly decompositions and specific sequences to be analyzed and selected based on their ability to deliver the product function and features. The method is applied to the upper skin assembly of the 767 horizontal stabilizer.

The technical basis for replacing fixtures in aircraft assembly is to provide features on the parts (called "mates" in Section 8) that are accurately located and capable of defining the assembly relationships between parts rather than depending on fixtures to do so. In the industry, such methods are sometimes called "precision assembly," "hole-to-hole assembly," and "determinate assembly." A major impetus to such systems, in addition to reducing the reliance on fixtures that are costly to build and maintain, is to do less manual drilling and riveting during assembly. These operations take a great deal of time. A question raised by the study that follows is whether these holes can be drilled with accurate enough locations that full assembly can be accomplished using them. Up to this time, most attempts at precision assembly have succeeded in tacking parts together with temporary fasteners, often using oversize holes in at least one of the two mating parts. The limiting factors at present are temperature fluctuations and the inherent accuracy of large machine tools. Tacking is the method assumed in this study.

11.1.1. Background

A flexible assembly system needs to meet several objectives. These include the ability to assemble a defined range of product variants within some class and the ability to meet the assembly tolerances and other requirements of each product in the class. Methods of assembly differ greatly depending on the physical size of the product and the production rate required. In this Section we study these issues for non-rigid products such as

[39] This section is based on the paper "Definition, Analysis, and Planning of a Flexible Assembly Process," by T. W. Cunningham, R. Mantripragada, D. J. Lee, A. C. Thornton, and D. E. Whitney, which appears in the proceedings of the 1996 Joint Japan-USA Conference on Flexible Automation, July 8-10, 1996, Boston MA.

airplane wing or fuselage skins, or automobile body sections. Such products would seem to differ greatly in production rate and thus require different kinds of assembly methods and equipment. However, they share more similarities than differences, the main ones being the need for fixtures and difficulty in achieving the required assembly tolerances.

Fixtures have traditionally been used to assemble these kinds of products for two reasons: 1) the parts are heavy and compliant, so they need support against gravity in order to obtain the correct shape, and 2) the fixtures are needed to provide dimensional references so that the correct dimensional and tolerance constraints are achieved between the parts. If any kind of flexible assembly is contemplated, the use of fixtures becomes a barrier because they are by nature dedicated to a single use rather than adaptable to a variety of products. If any alternate method is proposed, it must at least fulfill the above two requirements in addition to providing the desired type(s) of flexibility. Regardless of whether fixtures are used or not, each assembly must achieve certain dimensional and tolerance goals. The hood of a car must fit squarely and symmetrically between the front fenders, just as the skin of a wing must fit squarely and symmetrically between the leading edge and trailing edge subassemblies. The method, equipment, sequence, and measurement systems used in assembly must "deliver" these top level assembly requirements.

Aircraft and automobile structural assemblies are made of sheet metal, in contrast to small machined parts like engines or landing gear. Sheet metal is not only compliant, but in addition such parts in aircraft and automobiles usually lack well-defined or well-toleranced features that determine their relative positions and orientations after assembly. Machined parts usually arrive from the fabrication shops with "assembly features" already on them; e.g. a housing will have pockets where the ball bearings will be installed. Because sheet metal parts either do not have such assembly features or because the features cannot be made with enough accuracy or strength, fixtures usually play both roles: the fixtures contain the hard, well-toleranced mating features and are constructed in such a way that toleranced features on the fixtures are coordinated with each other, especially when several fixtures must be used one after the other for a final assembly.

In both the auto and aircraft industries there is dissatisfaction with single-use fixtures. They are expensive and thus have to be used for many years in order to pay for themselves. Often they wear during this time and need to be adjusted. Once an assembly line is built it is usually committed to one kind of assembly at one line speed. If demand for one product falls, its fixtures cannot be used to build another product whose demand exceeds its line's capacity. Attention is therefore turning to flexible assembly methods. In the past, robots have been successfully applied for small parts assembly, but

no economical robot flexible assembly method has been proposed for parts as large as those of cars or airplanes.

Recent work in this area has focused on seeking to give the parts for this class of assemblies some of the character of machined parts, that is, to give them some "assembly features" that can be used to locate them relative to each other directly (Ref. 1). This is not a straightforward process as it usually is with small machined parts because the parts in question here are large and thus greatly affected by temperature and manufacturing capability.

11.1.2. Approach

The method described in this Section focuses on carefully documenting the assembly requirements from the top level customer down to the fabrication of individual parts using the method of Key Characteristics (KCs). In addition, a set of assembly system analysis tools is described that help convert the KCs into specific assembly feature requirements, generate alternate assembly plans, and evaluate them according to their cost and capability to deliver the KCs in the face of a variety of dimensional variations in the parts. An example using a family of aircraft horizontal and vertical stabilizer skins (described in Section 11.2), is followed throughout the Section to demonstrate the method. On-site research was greatly assisted by Vought Center Division of Northrop-Grumman, The Boeing Commercial Aircraft Group, and the Ford Motor Company.

Figure 11-1 introduces the steps in our approach and shows where it is influenced by Product and Assembly Key Characteristics (PKCs and AKCs). We took as given the existing product and assembly decomposition. Our case study began by performing a flowdown of PKCs from high-level customer requirements to individual part features. Using these PKCs, AKCs were determined to relate the PKCs to the selected assembly decomposition with the results of steps 1, 2, and 3 described in Section 11.3. Based on the assembly decomposition, we also developed a set of all feasible assembly sequences utilizing an automatic assembly sequence generator (step 4) and pruned them into smaller sets called families (step 5). Steps 6 and 7 used the AKCs and sets of assembly sequences to identify the most promising family of sequences and perform a three-dimensional tolerance and cost analysis of several sequences with selected proposed assembly feature sets (steps 4 - 7 are described in Section 11.4). Once this was accomplished, detail process plans and equipment capabilities were explored, with two potential processes discussed in Section 11.5. A business case analysis is given in Section 11.6.

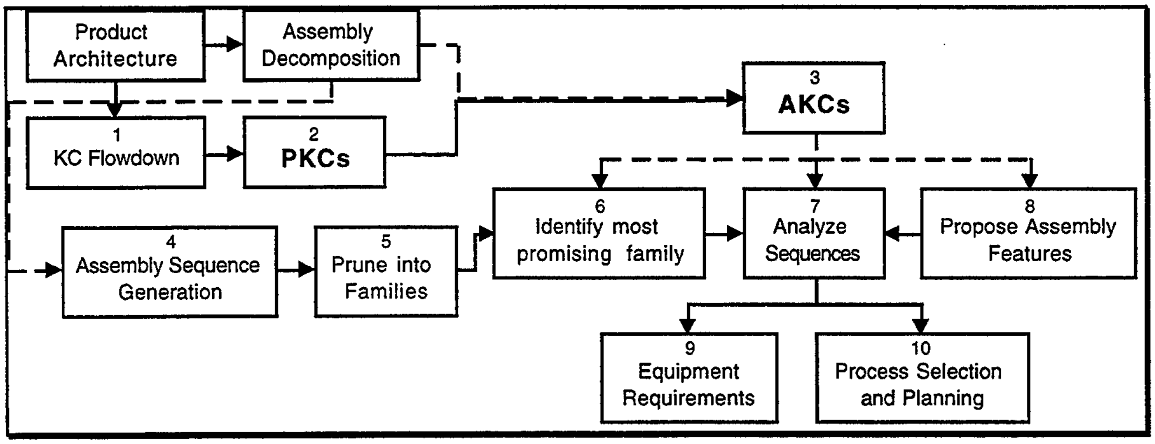


Figure 11-1. Approach to selecting the most promising flexible assembly process.

11.2. Product Description

The horizontal stabilizer is located at the aft end of the aircraft, enabling the aircraft to climb and descend by pivoting up or down to direct airflow, and balancing the moments of the aircraft (see Figure 11-2). The principal requirements for this structure are to carry to the aerodynamic loads while minimizing the drag it creates so overall system efficiency is maximized. The assembly can be thought of as three main assemblies: left and right wings and a center box. The stabilizer in this case study pivots about its long axis as a solid unit on two points, one at the aft end of each stabilizer, by the motion of an actuator that moves the front of the center box up and down. The horizontal stabilizer wings (see Figure 11-3 and Figure 11-4) are comprised of the following subassemblies:

- Forward Torque Box, including the forward spar
- Main Torque Box, consisting of:
- Pivot Rib at the root of the main torque box
- Upper Skin Assembly
- Lower Skin Assembly
- Ribs
- Fixed Trailing Edge, including the aft spar

Our case study is the family of upper and lower skins for several aircraft of similar construction but different in dimensions. The upper skin assembly is the example discussed in detail in this Section. It forms the top of the main torque box, the main structural body of the stabilizer shown in the exploded

view in Figure 11-4. This type of assembly is typically between 30 and 60 feet long and 5 to 10 feet wide.

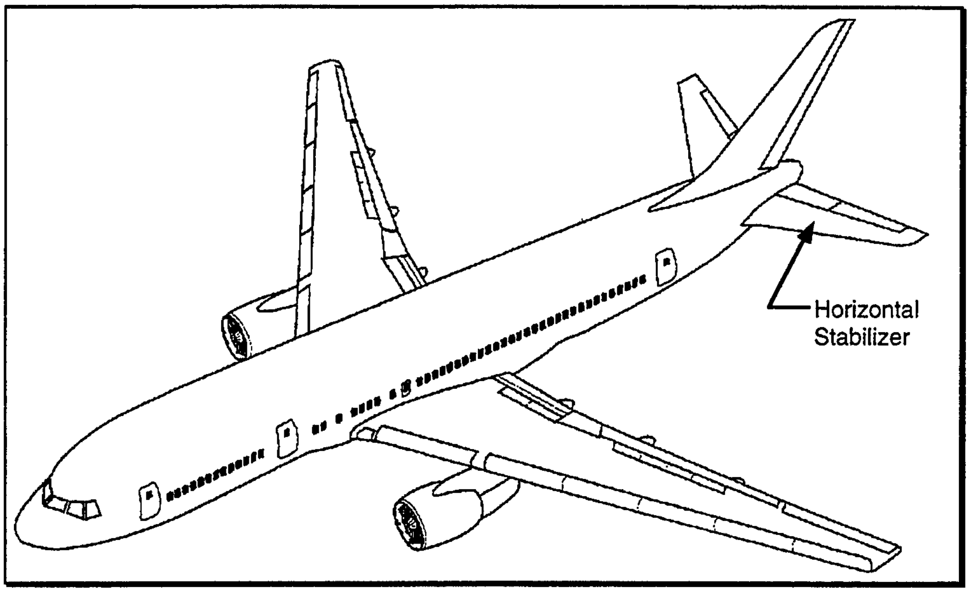


Figure 11-2. Horizontal Stabilizer position on the aircraft.

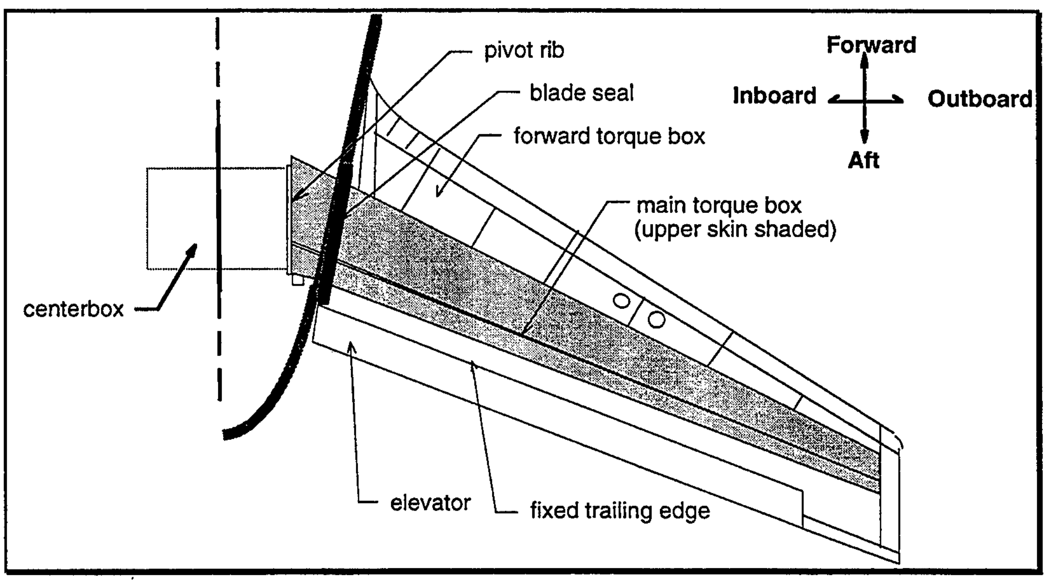


Figure 11-3. Horizontal stabilizer top view.

The main torque box sustains differential loads on the upper and lower surfaces and torsional loads along the length of the stabilizer. Figure 11-3 also denotes the reference frame used in this Section, showing the inboard, outboard, forward, and aft directions. As shown in Figure 11-5, the upper skin assembly includes the following parts, all of which are machined

aluminum and shot peened[40] to improve corrosion and fatigue crack resistance:

• Forward Skin - a long sheet of varying thickness that carries compressive and tensile loads and forms the aerodynamic surface.

• Aft Skin - similar to the forward skin; the aft skin acts as an access panel during assembly of the horizontal stabilizer.

• Stringers - long, slender beams that serve to stiffen the skins, with Z, I, or J cross-sections along the full length that minimize weight and maximize stiffness. They are riveted directly to the skin and fastened to the plus chord. Stringer #3 serves as a splice between the two skins (visible in Figure 11-5), while the other stringers are fastened to just one of the skins.

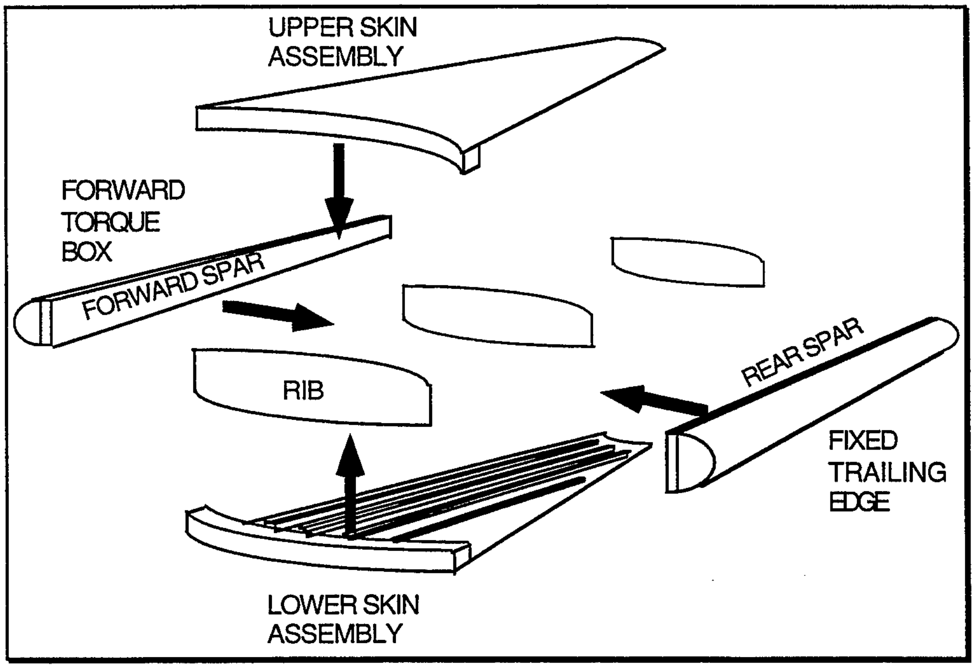


Figure 11-4. Exploded view of parts making up the horizontal stabilizer. The upper and lower skins, ribs, and spars (attached to the FTB and FTE) make up the main torque box.

[40] The shot peen process distorts the shape of parts after machining, with the most significant distortion being growth on the order of 0.0001 inch of growth per inch of length. This is a significant source of variation, and is common to all parts of this type in aircraft.

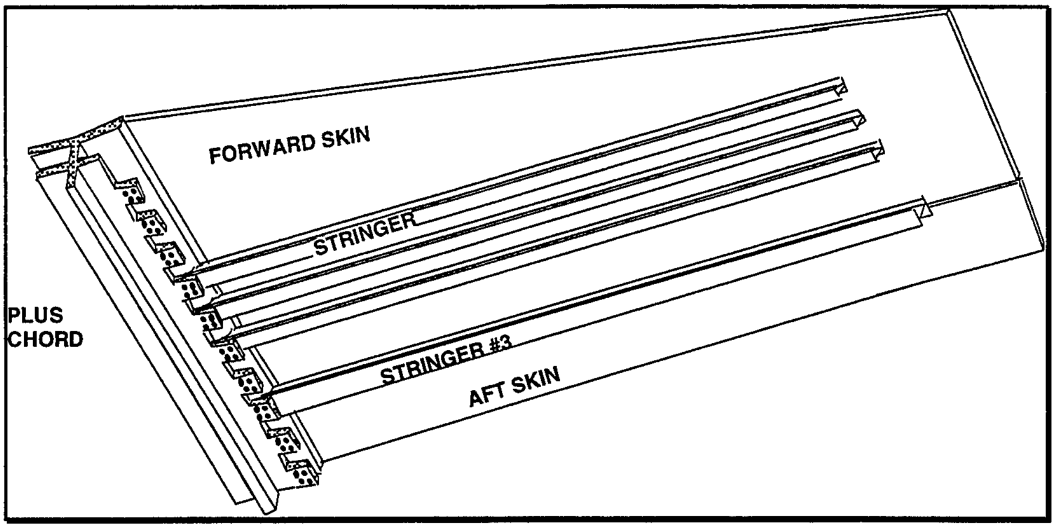


Figure 11-5. Skin assembly shown from the lower view.

• Plus Chord - a heavy heat-treated, machined extrusion that forms the top of the pivot rib at the root of the main torque box, where maximum loads in the stabilizer are absorbed. The complex geometry and intricate processing steps make the final shape of the plus chord difficult to control.

• Splice Plates (3) - form the top of the inboard end of the skin assembly and also absorb the large compressive loads.

The plus chord and splice plates join the left and right main torque box to the center box. Figure 11-6 shows a section view of the inboard part interfaces on the main torque box side of this joint, which is a mirror image of the interfaces on the center box side of the joint. Shims are used to fill assembly gaps between the plus chord and the stringer, with each made to a different thickness by hand. The actual skin assembly is contoured along the forward to aft axis, as represented in Figure 11-4, and along the length of the stabilizer.

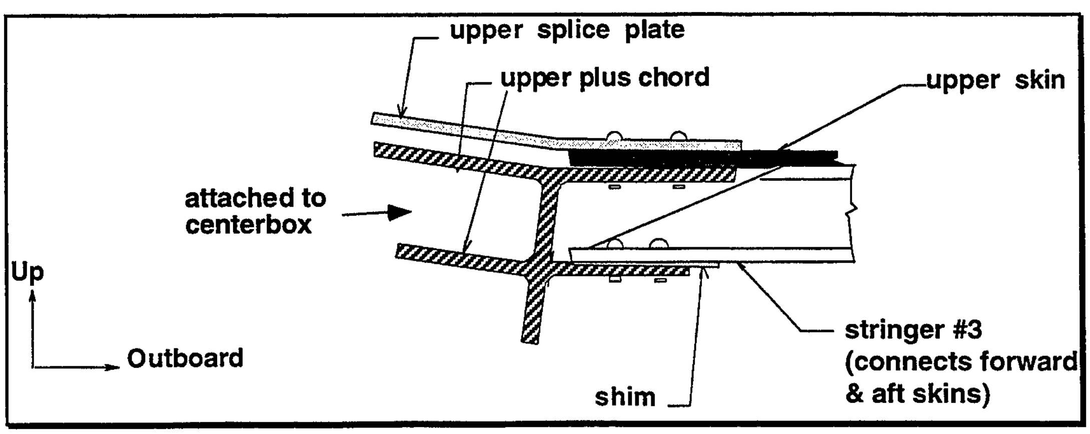


Figure 11-6. Inboard cross-section of the upper skin assembly and plus chord.

11.3. KC Identification for the Upper Skin

The first step in our study was to determine the KCs for the horizontal stabilizer. This section discusses the horizontal stabilizer PKCs that relate to the skin assembly, and the resulting AKCs. Figure 8 shows the product and assembly decompositions for the horizontal stabilizer, with focus on the sections of the main torque box, and the PKCs and AKCs discussed below.

11.3.1. Horizontal Stabilizer PKCs

The high level PKCs for the horizontal stabilizer mainly deal with aircraft drag and control issues from Federal Aviation Agency (FAA) regulations, aircraft loads carried by the structure as certified by the FAA, and aerodynamic specifications and airline customer requirements. Figure 11-7 shows the PKC flowdowns described below depicted in the center of the figure and shaded at the point where they affect our analysis of the upper skin assembly. The upper skin assembly is affected by load certification and aerodynamic requirements and these two issues produce three PKCs of importance to the discussion of AKCs below:

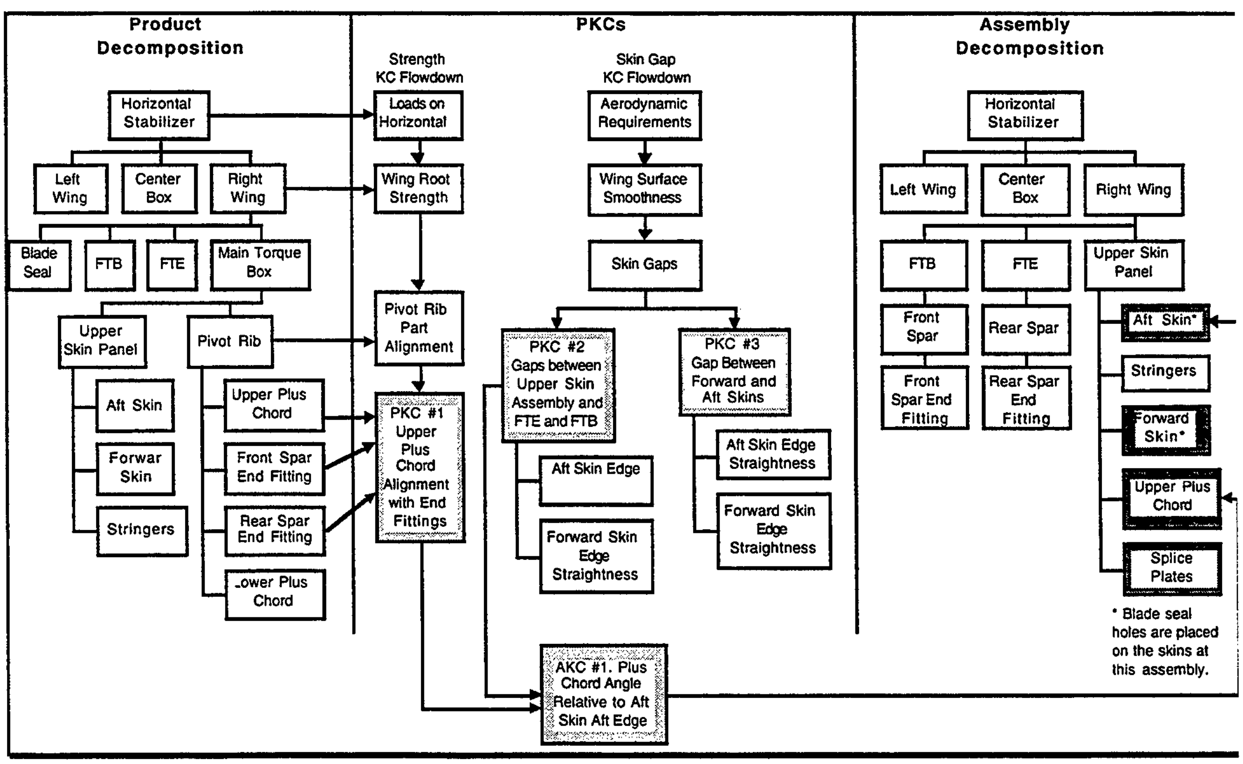


Figure 11-7. Product and Assembly Decompositions and resulting PKCs and AKCs.

• Structural loads require the parts making up the pivot rib be accurately aligned (dimensionally +/- 0.005in), which flows down to:

PKC #1: upper plus chord alignment to spar end fittings.

• The skin gaps must be accurate and consistent (nominal +/- 0.030in), which flows down to:

PKC #2: gaps between the skins on the upper skin assembly and those on the Forward Torque Box and Fixed Trailing Edge, and

PKC #3: gap between the forward and aft skins of the upper skin assembly.

Wing roots require very tight tolerance alignment of the plus chord to other parts of the root in order to properly absorb the dynamic distributed loads [Ref. 3]. This requirement is so important that, on some wing-like structures, if there is any alignment mismatch, a structural analysis is required to ensure that proper safety margins are maintained for that set of parts; this is costly but is required if fit-up is not achieved.

Skin gaps are critical to the smoothness of the wing because the sealant used to fill these gaps (creating a continuous surface for airflow) will flake out if the gaps are outside the specified tolerance

11.3.2. Horizontal Stabilizer AKCs

With the assembly decomposition fixed, and because the supplier does not envision changes to their downstream assembly processes, the current places where PKCs are coupled and where fit-up problems are possible remain important to the new process - these were identified as AKCs. We identified the places where PKCs are coupled by studying the assembly decomposition, and identified the potential assembly fit-up problems through interactions with engineers familiar with this class of assembly, by interviewing the mechanics at both subsequent assembly stations, and by studying the current assembly process.

Four AKCs were identified, with AKC #1 emphasized in our illustration of the method:

AKC #1 Plus chord angle relative to aft skin aft edge - when this angle is incorrect, either the plus chord does not align to the end fittings (PKC #1) or the skin assembly does not have the proper gaps with the Forward Torque Box and Fixed Trailing Edge skins (PKC #2), so time-consuming re-work is required. Figure 11-7shows the flowdown of PKC #1 and #2 to AKC #1, and how AKC #1 flows up through the assembly process. Figure 11-8 shows how PKC #1 and PKC #2 become coupled and depicts Figure 11-9 the angle identified as AKC #1 that delivers both PKCs.

AKC #2 Plus chord position fore/aft relative to the aft edge of the aft skin - when this is incorrect, its effect is not seen until final assembly of stabilizers to the center box when the mates between the stringers in the center box and the plus chord are attempted and the parts are found to be misaligned.

AKC #3 Inboard sandwich of the splice plates, skins, and plus chord (spacing and contour) - this is critical to a smooth join at final assembly and has a significant effect on gaps and gap consistency at final assembly, possibly causing time consuming re-work.

AKC #4 Blade seal hole locations relative to aft skin inboard edge (the blade seals are located to holes drilled in the upper skins) - The blade seal rubs tightly against the fuselage of the aircraft; this mate does not occur until final assembly, when re-work is most difficult and schedule risk is highest.

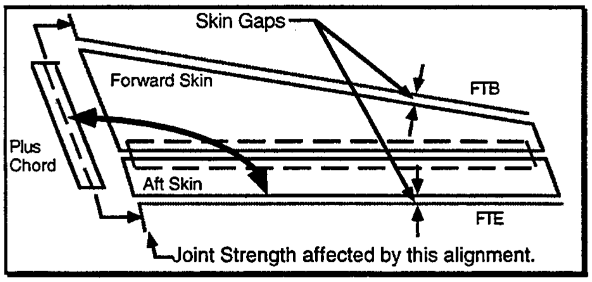


Figure 11-8. Coupling of PKC #1 and #2.

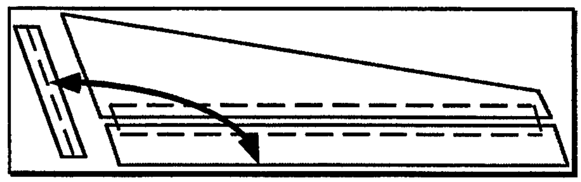


Figure 11-9. AKC #1

11.4. Tools and Methods Used in Assembly Process Definition

This section describes the current assembly method and the remaining tools used in the analysis: assembly sequence generation, sequence graph partitioning into families of sequences, and variation analysis.

11.4.1. Current Assembly Method

The main steps in the current assembly process are described below and Figure 11 depicts the size of the tack fixture relative to that of the parts. Cross-benchmarking has shown that this assembly process is similar to those for similar assemblies on other aircraft, with similar fixturing required.

• First stringers and then skins (separated by a tool to create the correct gap) are loaded into the contoured tack fixture, then "match drilled" along the length of the skin at approximately 18in intervals (approximately 15 holes per stringer). These are then riveted through the holes to maintain the contour once the assembly is removed from the fixture. It is important to note that this operation proceeds from outboard end to inboard, which causes the stringers to lose nominal location on the tooling locators inboard.- PKC #3 is delivered.

• The blade seal holes are drilled using a drill guide that attaches to the frame of the fixture. - AKC #4 is delivered.

• The plus chord is placed in the fixture and the operator locates the stringers to the plus chord by hand (because, as described in the previous step, the stringers are mislocated at this stage).[41] - AKC #1 and #2 are delivered.

• The splice plates are fixtured and the splice plates, skin, and plus chord are drilled in approximately 50 places for heavy threaded fasteners. The splice plates and plus chord are then disassembled, deburred, reassembled, sealed, and fastened. - AKC #3 is delivered.

• The assembly is then removed from the jig. Shims, each of a unique thickness that must be prepared by the mechanic, are placed between the stringers and plus chord; he then drills fastener holes through the stringers and plus chord.

• The sub-assembly is then taken to an automated riveter for most of the more than 1000 rivets.

Assembly of the full stabilizer structure is accomplished by loading the FTE and FTB in a large fixture to form the stabilizer shape. Each rib is put in place between the FTB and FTE, drilled, and riveted. Finally, the skin assembly is put in place and the entire structure is riveted. Assembly of the wings to the center box is accomplished by placing the wings and the center box on separate tools with limited axis motion capabilities. Next the wings are moved inboard to allow flanges to overlap the center box flanges (which is a mirror image of the root of the stabilizer shown in Figure 11-6). The assembly is shimmed and fastened.

[41] In addition to shot peen and thermal expansion, this is another source of variation that must be thought through before defining a self-locating set of features for this assembly.

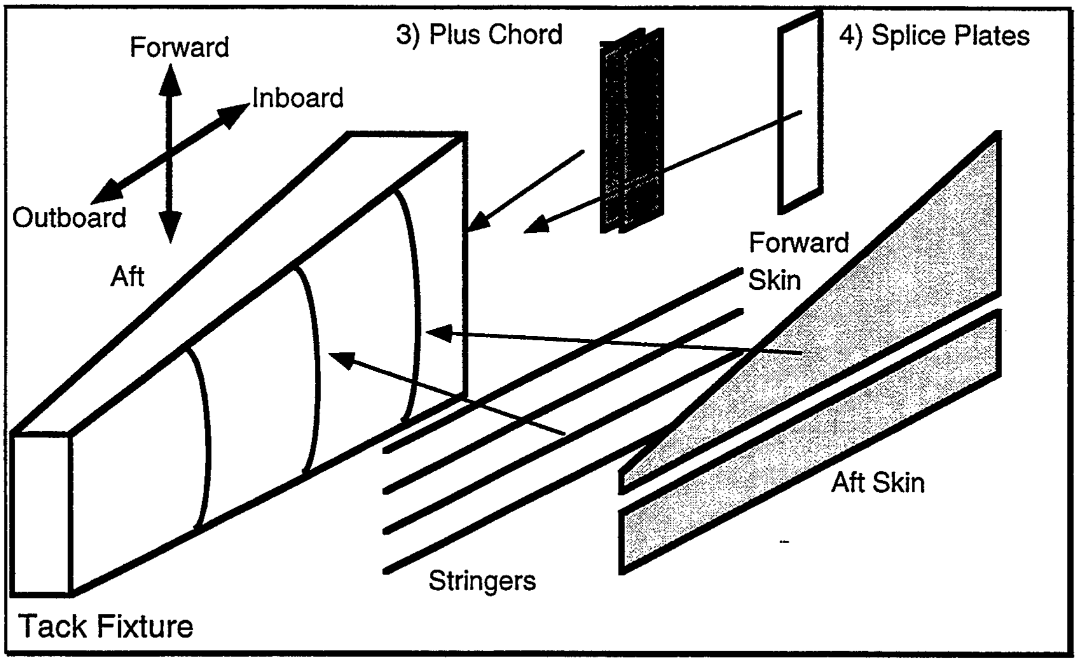


Figure 11-10. Current assembly sequence in the dedicated tack fixture.

The assembled horizontal stabilizer is then joined to the aft fuselage section and the interface is tightly sealed by putting the blade seals into the blade seal holes on the skins.

11.4.2. Extension of the Current Method to a Flexible Method

The current method described above relies on expensive hard tooling to establish part locations, operator intervention to overcome part and process variation, and custom shimming to fill inconsistent assembly gaps. Although the process delivers an acceptable product for the downstream assembly process, it is completely inflexible and an expensive way to achieve it.

To make the assembly process more flexible and independent of hard locating fixtures, a flexible assembly concept was explored. This concept is based on using accurate mating features on parts to locate other parts that they mate with in the assembly. These features are called "assembly features" as their primary function is to locate a part with respect to its mating parts. Without any analysis, we could define a set of tightly toleranced features on every part to be used during assembly so all mates would be accomplished. For example the upper skin assembly could be constructed by drilling accurate holes on the skins and stringers, and simply pinning these features together during assembly. However, because these parts are very long and are subjected to variations caused by thermal expansion and the shot peening process, a closer look shows that this approach would require high capability machines to create all these features, increasing the manufacturing costs. In

addition, a careful examination of the AKCs reveals that there are no AKCs associated with the skin-stringer interface and so it is really not very critical to control this interface. Other interfaces are critical; e.g. the plus chord-skin interface achieves AKC # 1 and #2. Assembly features such as edges, surfaces, holes, and slots are all candidates. Any choice of these must be tested using tolerance analysis to verify their ability to deliver the AKCs.

We propose a more structured and methodical approach to flexible assembly. Instead of tightening tolerances on every set of mating features on all the parts, we focus on the part mates that are associated with the realization of the AKCs. The proposed method uses the set of identified AKCs to design part features and the processes that realize the assembly, with focus on the AKCs so the critical interfaces are tightly controlled.

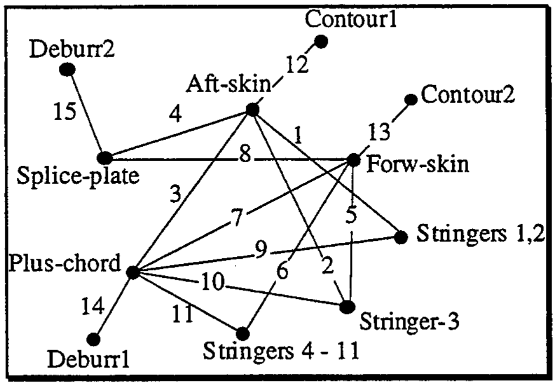
The approach starts by identifying a set of AKCs that would realize all the PKCs for the assembly (which were presented in Section 3). A complete set of feasible assembly sequences are then identified for the assembly from which the sequences that best deliver the AKCs are identified. These selected assembly sequences and several proposed assembly feature sets are then evaluated for process planning issues, tolerance stackup, etc. to finally identify the best few sequences that control the right interfaces to repeatably deliver all the KCs, without driving the costs too high. The following sections describe each of these steps in detail.

11.4.2.1. Assembly sequence generation

Once the AKCs for the assembly are identified, the next step is to identify an assembly sequence or a set of sequences that will deliver the AKCs. An assembly sequence generation software (ASA) [Ref. 4] was used to generate all possible sequences for the assembly. Assembly sequence analysis began by constructing the liaison diagram of the assembly shown in Figure 11-11a. The nodes in the graph are parts and the arcs are the liaisons (contacts or mates) between them. Since the assembly involved some fabrication processes like contouring and deburring, they too were treated as nodes in the liaison graph. In addition, the disassembly of the splice plates, plus chord and the skins after assembly for deburring was also represented using this graph. From the liaison diagram the precedence constraints (what parts /processes should be assembled/performed before what other parts) were generated by answering a series of Yes/No queries from the software. These precedence constraints were used to generate the assembly sequence graph (Figure 11-11b) showing all feasible assembly sequences for this assembly [Ref. 5]. Every box in the graph represents a feasible assembly state and every path from the top to bottom of the graph represents a feasible assembly sequence. At every level, one part is added or one process is performed on the assembly. There were 1507 unique feasible assembly sequences identified for this assembly using the ASA tool.

11.4.2.2. Generation of families of sequences

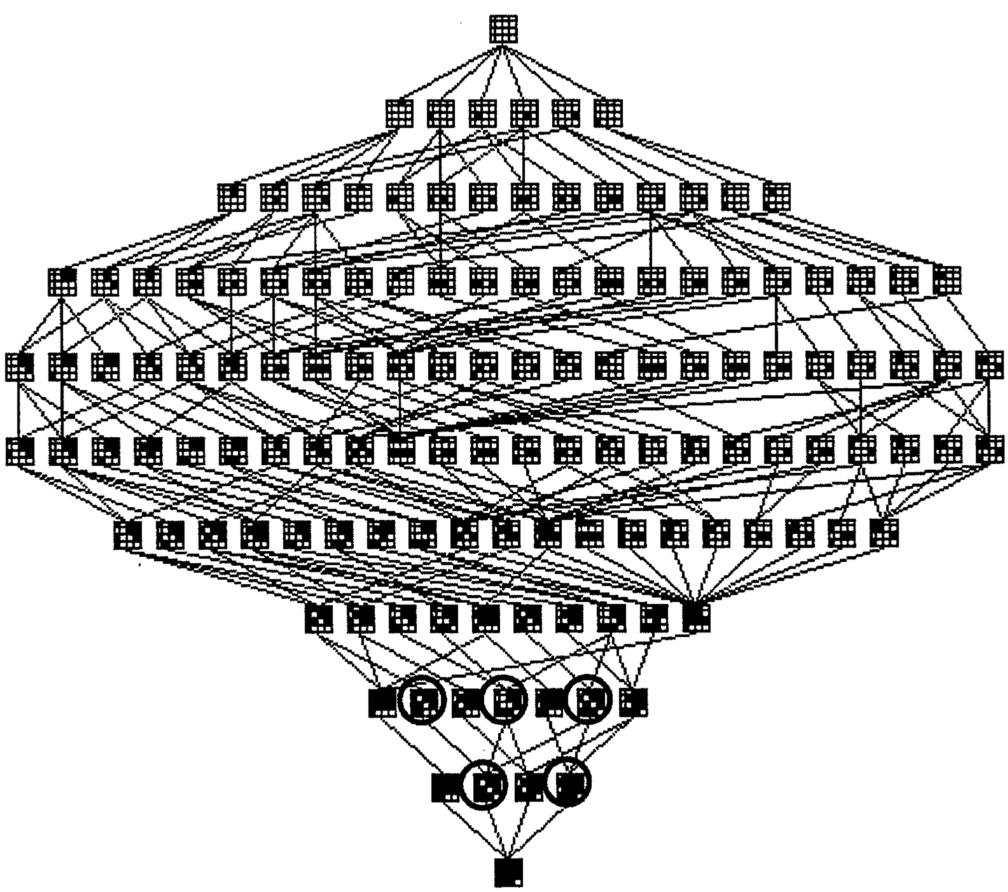
Not all of these feasible sequences can successfully deliver the KCs because different sequences tend to control different part interfaces. It is not clear from the complete graph which sequences deliver the KCs repeatably, and the



1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	

LIAISON KEY

a.



b.

Figure 11-11. Assembly sequences were generated using the liaison diagram, shown in (a). The sequence diagram shown in (b) includes all possible sequences, and was pruned to three families.

evaluation of the entire set of 1507 sequences presents a time-consuming task. Therefore, an approach is needed to assist in pruning the graph into smaller sets of sequences to be evaluated.

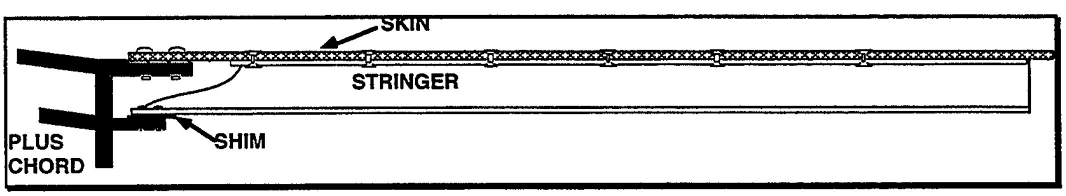
The approach is based on dividing the set of feasible assembly sequences into families. Each family is associated with the sequence in which the major mates are accomplished: skin-to-stringers, skin-to-plus chord, and stringers-to-plus chord. Each family achieves the AKCs in different ways and imposes different requirements on process and assembly planning. Because these three mates form a closed loop, the quality of the fit of the first two can be controlled, but the quality of the third mate is determined by accumulated variation in the assembly features and process equipment associated with the first two. Therefore, important KCs should be associated with the first two mates, and the resulting uncertainty should be absorbed or "washed out" in the third. Once this idea was used to generate the three families, the challenge was to find the most promising family and then the most promising process sequences from that family.

The families generated are as follows (see Figure 11-12):

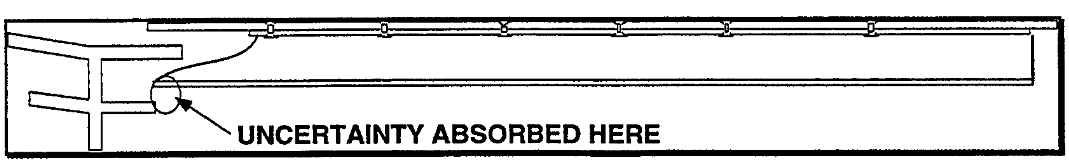
- Family-1: Skin-based: [408 sequences] Mate all parts to the skin and accumulate the variation for the assembly at the plus chord-stringer interface.

- Family-2: Stringer-based: [569 sequences] Mate all parts to the stringers and accumulate the variation at the skin-plus chord interface.

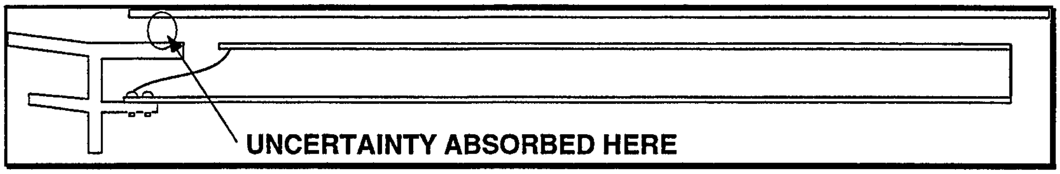
- Family-3: Plus chord-based: [530 sequences] Mate all parts to the plus chord and accumulate the variation at the skin-stringer interface.



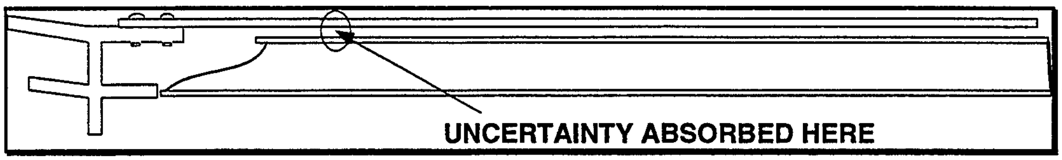
a. Nominal Configuration



b. Family-1.



c. Family-2.



d. Family-3.

Figure 11-12. Possible locations for absorbing variation.

11.4.2.3. Pruning and identification of the most promising family

The next step is to evaluate the generated families for their ability to deliver AKCs, required tooling, and manufacturing process requirements. By evaluating these issues for the different families, instead of for a large number of sequences, we simplify our search for the best sequence and features by limiting the search space to a promising family.

First, the generated families were pruned further by eliminating difficult states and operations, and imposing specific precedence constraints. This resulted in a manageable set of sequences in each family that would be subjected to subsequent sequence analysis for selection of a suitable sequence:

- Family-1 edited set: Number of sequences = 44
- Family-2 edited set: Number of sequences = 11
- Family-3 edited set: Number of sequences = 32

We next considered the potential for each of these pruned families to deliver the KCs. At this point, it was not necessary to select specific assembly features, just to consider the sequence of mates. We found Family-1 was the closest to the framework for the current process (recall the operator absorbs the variation at the plus chord-stringer interface by hand) and has the potential to deliver the critical AKCs because the skins and plus chord are located relative to each other. An important negative attribute is that variation is absorbed inboard - where strength is most critical and pre-load is least desirable. Because this process requires operator intervention to achieve

the stringer to plus chord mates, we eliminated it from further explicit investigation, but kept it as a possible fallback option. Family-2 fails to deliver two AKCs because it does not control the skin to plus chord interfaces; this family warrants no further consideration. Family-3 explicitly delivers the skin-plus chord AKCs and the variation is washed to the skin-stringer interface, which we found to be the least critical location, so it appeared to be the most promising family.

Various sequences for Families-1 and -3, with Family-3 appearing to be the most promising, formed the input for three-dimensional variation analysis.

11.4.2.4. Three dimensional tolerance analysis of family 3 using VSA

Once Family-3 was identified as the most viable approach to satisfying the AKCs, we sought to evaluate possible sequences and sets of assembly features to determine which sequences could most repeatably deliver the AKCs, and hence the PKCs. We used Variation Simulation Analysis (VSA), a 3D tolerance analysis program that performs Monte Carlo simulations by varying product tolerances of a user specified distribution and analyzing interfacing features of the product.[42] VSA is currently used with increasing success in the automotive industry [Ref. 7], but 3-D tolerance analysis of this sort has only had limited success to date with aerospace companies due to the apparent complexity of the analysis. VSA is a robust, marketed piece of software that can be used as a proxy in our method for any suitable tolerance analysis approach. This demonstration shows how, when a problem can be focused (e.g. on AKCs), a large task like a complete VSA simulation can be simplified to study only the most important aspects of the problem - predicting the ability to deliver AKCs.

The analysis began with construction of a nominal skeleton of the parts with representative dimensions. Next, the variations of the parts were represented based on actual machine and fastening capabilities obtained from on-site research at the supplier, for both existing machines and potential future equipment. The AKCs then became the dimensions VSA was used to measure. Finally, several runs with different assembly sequences and candidate assembly features were performed to analyze the ability to deliver the AKCs. The VSA results are summarized in Section 11.5.

11.5. Two Flexible Assembly Process Candidates

A major benefit of a flexible assembly system is minimization of non-recurring costs by eliminating the assembly tooling design and fabrication

[42] The authors wish to thank Variation Systems Analysis, Inc. for the opportunity to evaluate the software under a no cost academic evaluation license.

costs for other new or variant products. For existing products, however, this non-recurring savings is not realized because fixtures already exist, so cost benefit must be realized with time savings at assembly. Discussions with the supplier of these assemblies showed that cost savings on existing products would be a challenge, and it became clear that existing fabrication equipment would need to be used as much as possible to reduce up front investment costs.

This section describes two processes that can achieve the AKCs, but have different cost and ability to deliver the AKCs repeatably. Figure 14 shows the approach to absorbing variation used by both processes - both are of Family-3 so variation is absorbed at the skin-stringer interface. The first process utilizes no dedicated fixtures or tools and maximizes the use of existing fabrication equipment; however, this process is not predicted to deliver AKC #1 with 100 percent repeatability, so selection of this process will require re-work on some parts. The second process defines a limited number of small fixtures to used with flexible machines required to repeatably deliver AKC #1. Both processes are expected to be able to deliver all other AKCs and PKCs. Both processes require investment in capital assembly equipment, with proposed process #2 requiring a higher degree of functionality in that equipment, and both result in a high-level of flexibility in the assembly of the family of skin panels. Table 11-1 summarizes the two processes, comparing them to the existing process. Table 11-2 summarizes the pros and cons for the two proposed process compared with the current process.

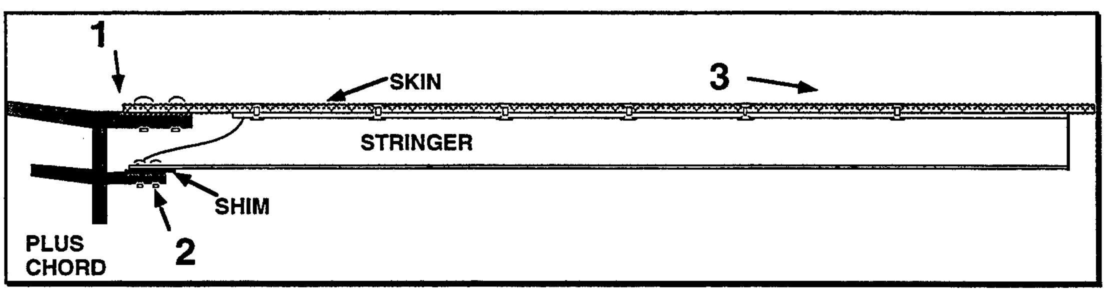


Figure 14. Approach selected for the two proposed processes, with the skin-stinger mates accomplished last.

Current Process	Proposed Process #1	Proposed Process #2
Load stringers on vertical tack fixture, which provides location and contour	Load aft skin on vertical "flexible contour fixture"	Load skins bottom-up on horiz. "flexible contour fixture" - gap established by a tool (PKC #3)

Load skins, gap established with a shop tool (PKC #3)	Tack stringer 3 to aft skin through holes on stringer, slots on skin	Load splice plates to a fixture inboard
Match drill and rivet skins to stringers	Tack forward skin to stringer 3 in same manner - gap established by separation of stringer holes	Tack stringer 3 to one hole on forward skin inboard, CNC position, match drill, and fasten skins to stringer 3
	(PKC #3)	
Drill blade seal holes (AKC #4), location established by fixture	Match plus chord and splice plates to holes and slots on parts (AKC #1, 2, 3)	Place a small tool on the plus chord at forward end
Load plus chord (AKC #1 & 2), location established by fixture. Match stringers to plus chord by hand.	Tack each remaining stringer to one hole on plus chord scallop (and shim) and slots along length of skins	Tack plus chord through a hole in aft skin, match surface of small tool to inboard edge of forward skin (AKC #1 & 2)
Load splice plates (AKC #3)	Autorivet, drill through splice plates, skins, and plus chord, drill blade seal holes (AKC #4)	CNC drill through plus chord, skins, and splice plates, remove tool from plus chord (AKC #3)
Drill, disassemble, deburr, seal, fasten inboard parts	Drill remaining stringer to plus chord holes	Tack remaining stringers to one hole on plus chord scallop (and insert wedge)
Shim stringers to plus chord	Disassemble, deburr, seal, fasten	NC drill and temp fasten stringer
	inboard parts	to plus chord holes
Autorivet		CNC position, match drill, and fasten skins to stringers
		Autorivet, drill through splice plates, skins, and plus chord, drill blade seal holes (AKC #4)

		Disassemble, deburr, seal, fasten inboard parts Shim stringers to plus chord

Table 11-1 Assembly Process Comparisons - Summary

	Current Process	Proposed Process #1	Proposed Process #2
Pros	• Delivers all AKCs and PKCs repeatably	• Delivers AKC #2, 3, 4 and PKC #3 repeatably • Completely flexible method • No dedicated fixtures • Uses existing fab equipment • Least costly • Controls critical interfaces	• Delivers all AKCs and PKCs repeatably • Completely flexible method • Uses existing fab equipment • Controls critical interfaces
Cons	• Inflexible fixtures • Variation absorbed at stringer-plus chord interface	• Fails to deliver AKC #1 on a few assemblies • PKC #1 & #2 not delivered on those same assembies	• Requires higher-functionality tack fixture (higher cost) • Requires a limited number of small fixtures

Table 11-2. Pros and Cons for the Current and Two Proposed Processes

11.5.1. Proposed Process #1: Utilizing Existing Equipment

This process is intended to match the supplier's investments and investigations to date. With minimum equipment investment as a goal, the process recommended here attempts to focus on delivering the AKCs, but seeks to utilize existing fabrication equipment capabilities at the plant as much as possible, while limiting the investment in new flexible tooling and equipment for the new process. Significant VSA modeling was conducted, and the trade-offs are discussed below.

11.5.1.1. Part features and equipment requirements for proposed process #1

Proposed process #1 requires the creation of assembly features during part fabrication. Several proposed feature sets were evaluated with VSA, with the selected features shown and labeled by numbers in Figure 11-13. Proposed Process #1 mating features. representing the AKCs this sequence and feature set produces:

• Forward Skin - machined on the current milling machine, with the addition of the following features referenced to the inboard and aft edges and created prior to shot peen:

1. slots machined along the aft edge (parallel to that edge) to integrate with holes machined on stringer 3,

2. slots machined elsewhere along the length of the skin to integrate with holes on other stringers, and

3. 1 slot and 4 oversized holes to mate with splice plates and plus chord.[43]

• Aft Skin - machined on the current mill, with the addition of the following referenced to the inboard and aft edges and created prior to shot peen:

4. slots machined along the forward edge to integrate with holes machined on stringer 3,

5. slots machined elsewhere along the length of the skin to integrate with holes on other stringers, and

6. 1 precise diameter hole and 1 oversized hole to mate with aft splice plate and plus chord.

---

[43] The oversized holes are not used for location, just to clamp the plus chord, skins, and splice plates with temporary fasteners.

• Stringer 3 - machined on current spar mill with the addition of one hole (not visible in Figure 11-13) to mate with plus chord. Additional features machined on a different mill (due to the more stringent tolerance requirements discussed below) also prior to shot peen:

7. holes machined along length to attach to both skins - hole tolerance requirement is discussed below.

• Other stringers (not shown in Figure 11-13) - machined on current spar mill, with addition of holes machined along length of stringer to attach to skin and one hole machined on each to mate with plus chord, then current shot peen and other processing.

• Plus Chord - machined on the current mill, with the addition of one hole to mate with each stringer (not visible in Figure 11-13), and

8. seven holes to mate with skins and splice plates.

• Splice Plates - machined on current mill, with the addition of:

9. one hole and two slots on the aft splice plate, and

10. two slots on each of the other two splice plates.

Proposed Process #1 skin assembly[44] is summarized in Table 11-1. Figure 11-14 summarizes the relationship of the PKCs, AKC #1, and the assembly feature AKCs for this process.

[44] We credit the supplier for the equipment concepts in this method. Our method documented the KCs and determined the correct sequence and features to utilize these tooling concepts within the constraints of the AKC requirements and manufacturing process capabilities.

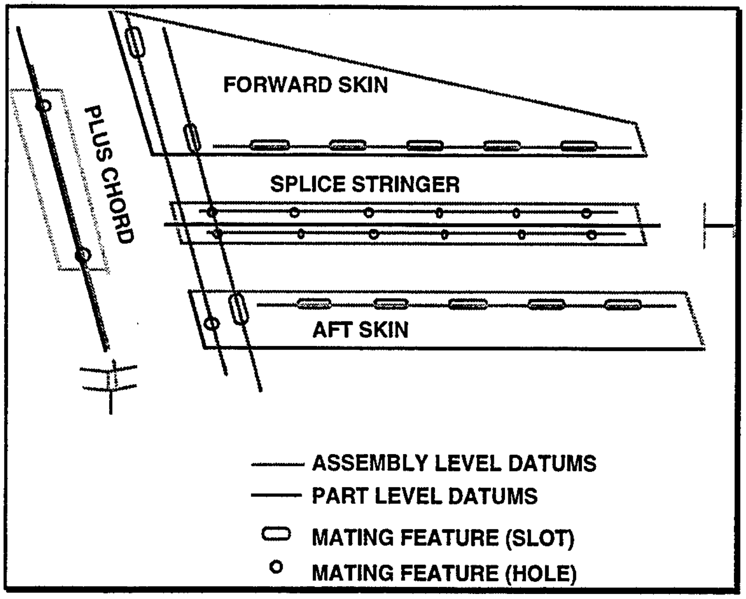


Figure 11-13. Proposed Process #1 mating features.

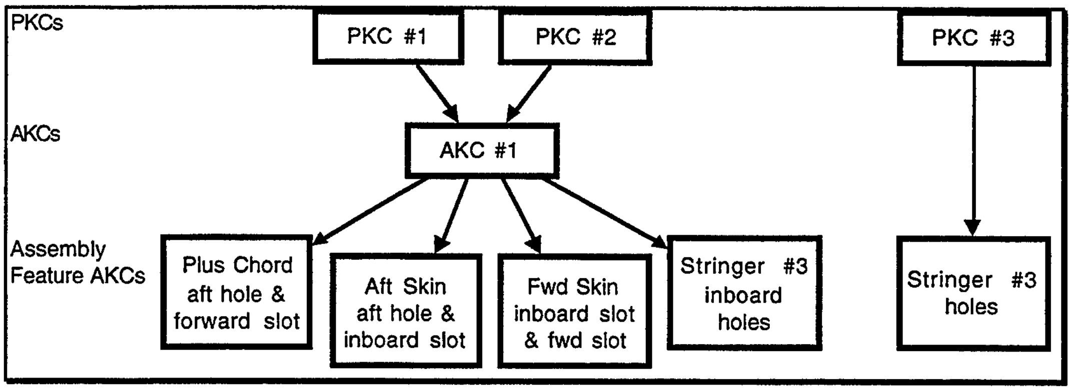
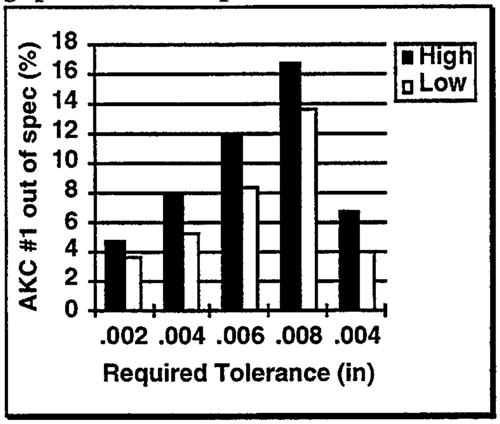
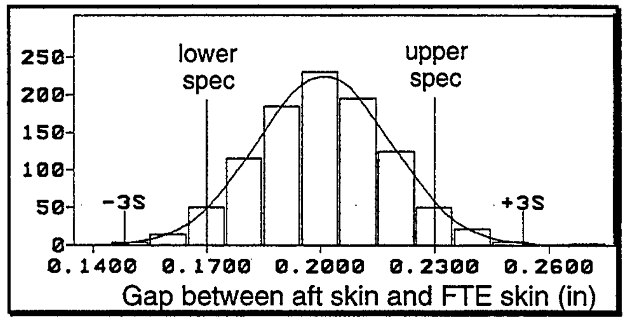


Figure 11-14. PKC and AKC relationships for Proposed Process #1.

VSA predictions for this assembly method showed that the critical tolerance in the process is on the location of the holes in stringer #3 used to determine the gap between and inboard-outboard positions of the two skins; these slots have significant effect on the relative position on the skins, and hence on the plus chord position which is referenced to the aft hole on the aft skin and slot on the forward skin (as shown in Figure 11-15). VSA simulations were conducted for several vales of this tolerance. Figure 11-15a shows the number of assemblies failing to deliver AKC #1 plotted against the tolerance value of the stringer hole positions for each VSA simulations. The first four are predictions with no improvements to any fabrication equipment. The fifth entry requires a relatively low cost improvement to the skin mill that the supplier is considering to improve its positional accuracy. If this improvement is made, then +/- .004, C_{pk} = 1 is the recommended requirement because it is potentially achievable with existing equipment. In this case, stringer #3's holes could be created on the skin mill after its initial fabrication on the spar mill.

With this tolerance, 100 percent of the assemblies are predicted to deliver the gap between the two skins, but 10.7 percent of the assemblies will *not* deliver AKC #1. Despite this weakness, this process was selected as the best solution when cost is considered. Figure 11-15b shows the predicted distribution of skin gaps with this process, with 0.200in representing the nominal gap dimension.





a. b.

Figure 11-15. VSA results for proposed process #1 - (a) shows five predictions for different stringer hole position tolerances, (b) shows the statistical prediction for the recommended case (1000 samples).

While our focus is to deliver the AKCs, this process represents the limitation of the concept of creating "assembly features" at the independent part fabrication steps. In order to analyze this further, additional VSA simulations were conducted with stricter tolerance requirements, to the extreme case where new mills all with 0.002in positional accuracy were assessed. Even at these extremes, 3 to 5 percent of the assemblies are still predicted to be out of tolerance. These machines would represent a significant equipment investment, but their ability to deliver AKC #1 remains limited.

11.5.1.2. Scenario for selecting process #1

The supplier would be inclined to select this process if some amount of re-work or out of tolerance conditions are allowable. The supplier is not allowed to fail to deliver the PKC concerning plus chord alignment, but can waive high skin gaps. If there is a contractual penalty associated with failure to deliver the skin gap, then the number of assemblies predicted to be out of spec, and hence the cost penalty, along with the cost of shimming the assemblies with a low skin gap, could be traded against the cost of a better machine to more accurately produce the features that most affect that gap - the hole positions on stringer #3 and the skin edge and hole position tolerances.

11.5.2. Proposed Process #2: Defining Equipment to Deliver all AKCs 100% of the Time

Proposed process #2, also summarized in Table 11-1, is an assembly approach that defines the equipment needed to deliver the AKCs repeatably. The concept uses a horizontal flexible contour bed utilizing inboard fixturing to align the plus chord and splice plates and a CNC drilling capability to match drill the interfaces of the skins to stringers and plus chord, skins, and splice plates. The concept is fundamentally different than proposed process #1 because very few assembly features are created on the parts during fabrication. Instead, proposed process #2 represents an automated, flexible method of accomplishing match drilling and tacking while accurately locating the parts with a limited amount of small, dedicated fixturing so the interfaces that deliver the KCs are tightly controlled. Figure 11-16 shows the only features required to be created on the parts.

11.5.2.1. Part features and equipment requirements for proposed process #2

Proposed process #2 requires the creation of the following assembly features during part fabrication. The features shown and labeled by numbers in Figure 11-16 are the AKCs this process produces, and the relationship between the PKCs and AKCs are shown in Figure 11-17. Shot peen and other processing are unchanged.

1. Forward Skin - machined on the current mill, with the addition of one hole inboard to mate to stinger #3.

2. Aft Skin - machined on the current mill, with the addition of 1 precise diameter hole to mate to plus chord.

3. Stringers - machined on current spar mill, with one hole machined on each to mate with plus chord.

4. Plus Chord - machined on the current mill, with the addition of one hole aft to mate to the aft skin and one hole to mate with each stringer.

5. Splice Plates - machined on current mill, with the addition of 2 holes per plate to mate to features on the contour bed.

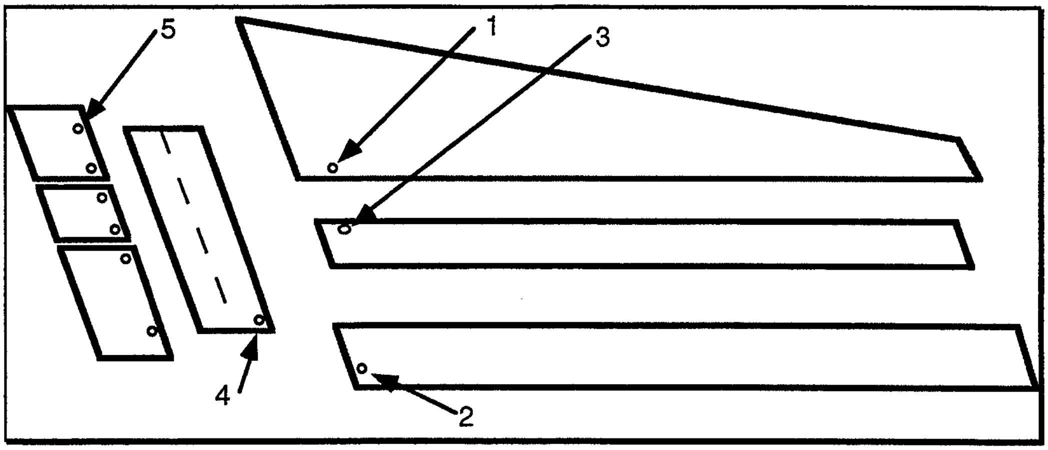


Figure 11-16. Part features for proposed process #2.

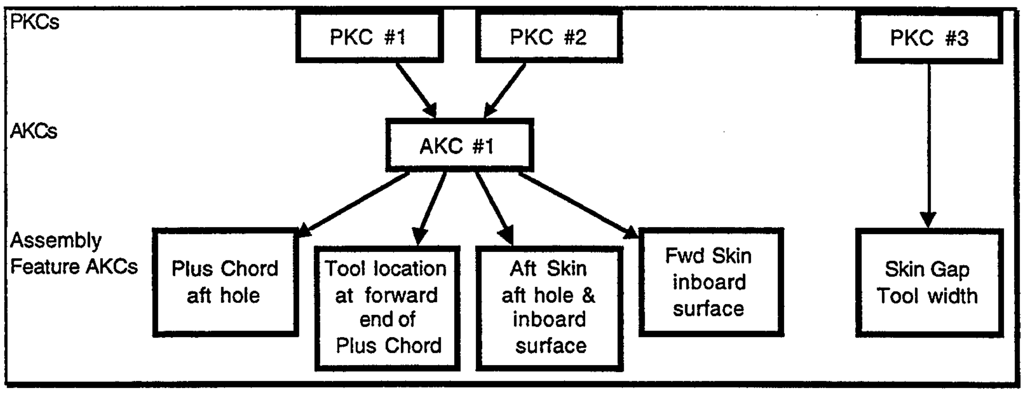


Figure 11-17. PKC and AKC relationships for Proposed Process #2.

11.5.2.2. Scenario for selecting process #2

While this concept represents a way to repeatably deliver the AKCs, it fails to completely eliminate dedicated tooling and requires significant equipment investment. The supplier should select this process if the cost penalty for AKC #1 requires that the process must deliver this AKC 100 percent of the time. This process represents the most economical approach to achieving 100 percent delivery of AKC #1 because it requires no equipment investments for part fabrication, just a higher level of equipment investment for assembly than that shown in proposed process #1. Proposed process #2 is achieves the goals of a flexible assembly system because it supports the full family of assemblies and eliminates all dedicated large fixtures, requiring only a small number locating devices to assist the process.

11.6. Business Case Analysis

A business case analysis was done to determine a) how one should use economic analysis to determine if an investment in flexible assembly is

justified and b) to see if it is justified in this case. The basis of the analysis was the following set of assumptions

1. The base case for comparison was the then-existing manual process (called "as-is")

2. Three candidate automated flexible processes were compared to the base case. Each candidate is a concept comprising process steps, required mating features machined onto the parts, and various pieces of drilling and riveting equipment. One of these is a process proposed by Vought. The other two are called MIT 1 and MIT 2, as detailed in Table 11-1.

3. Only the 767 skin subassembly was studied in detail. Conclusions from this study were extrapolated to similar products made for other aircraft.

11.6.1. Methodology

The methodology involved assuming several production scenarios, some involving switching current business from manual to automated processing, others assuming new business would arrive.

Process times were estimated for three manufacturing cells: one that tacked the parts together, one CNC autoriveter, and one final assembly cell. Process times were estimated for each machine based on performance of similar equipment observed in the industry. A computer simulation was used to determine the overall capacity of all three cells, including transport capacity between them. Based on the different business scenarios, required investment in equipment to meet production requirements was calculated.

Two studies were conducted within the above scenarios. In the first, only four parts were included in what could be called a pilot program. In the second, all parts made for Boeing 747, 757, and 767 horizontals were included. In each case, one and two shift operations were studied.

11.6.2. Results

Based on a variety of simulations, each of the proposed automated cells reduced process flow-through time by around 50%. The savings from this were attributed entirely to labor costs and amount to about 13000 hours per year. No savings were attributed to work in process inventory, which of course would be substantial. If we take a representative number of $100 fully loaded cost per labor hour, the savings amount to approximately $1.3 million per year.

Equipment investment requirements were based on estimated equipment costs as shown in Table 11-3:

Process Name	Tack Cell	Auto-Rivet Cell	Final Assembly
MIT 1	$2 million	$4.8 million	$0.5 million
MIT 2	$3.5	$4.8	$0.5
Vought*	$2	$4.8	$0.5

Table 11-3 Equipment Investment Required for Precision Assembly. *Vought process requires additional $4 million for improved fabrication equipment.

The total number of each kind of machine needed, based on simulating the different scenarios is shown in Table 11-4.

Scenario	Tack Cell(s)	Auto-Rivet Cell(s)	Final Assembly Cell(s)
1 shift/all parts	3	3	2
1 shift/4 parts	2	2	1
2 shifts/all parts	2	2	1
2 shifts/4 parts	1	1	1

Table 11-4 Equipment Requirements for Different Scenarios for MIT Processes 1 and 2.

A comparison of equipment requirements and utilization is given in

Cell	Vought		MIT 2		MIT 1	
	1 shift	2 shifts	1 shift	2 shifts	1 shift	2 shifts
Tack	4/89%	3/60%	3/70%	2/53%	3/65%	2/49%
A-R	3/89%	2/67%	3/90%	2/68%	3/93%	2/70%
Final	2/72%	1/73%	2/72%	1/74%	2/80%	1/82%
Total cells	9	6	8	5	8	5

Table 11-5. Equipment Requirements for All Boeing Parts and their Utilization

11.6.3. Summary Findings

The attributed savings of $1.3 million do not provide an attractive rate of return for the estimated investment. Several mitigating factors need to be taken into consideration. The above analysis is conservative in attributing savings, because it does not credit the automated processes with any savings due to work in process inventory or quality. (The existing manual process produces corretly made assemblies and Boeing has no complaint about them. Internal rework data for the manual process were not available for this study.). Second, should new business arrive, a great deal of savings can be anticipated, although three shift operation might be necessary due to the high rates of utilization under the existing business scenario. Third, no provision was made in this analysis for savings possible should there be a change in product demand mix. In the existing manual environment, there is no way to utilize 747 fixtures for 757 parts, for example. The new equipment is assumed able to do any part from any of the aircraft. Fourth, there was no attribution of savings in floor space, whereas the new equipment would replace many existing fixtures spread over a large floor area. Finally, no savings were attributed to the image of advanced manufacturing that the new processes and equipment would provide.

The result is that a management decision is required, involving additional studies to see if the omitted factors make the investment attractive based on pure business terms or based on that plus the marketing appeal of a new method.

11.7. Conclusions

Assembly system planning is a critical decision period that will have lasting effect on product cost and quality. Like any design problem, successful assembly system planning requires recognition of design requirements and a sound up-front approach to trade-offs . This Section demonstrates a structured method to perform a holistic process for designing complex assemblies.

The case study produced two proposed approaches to flexible assembly of large aircraft skin structures, with a focus on delivering the critical interfaces while minimizing cost where possible. The two approaches are the input for an important decision, trading off equipment investment and repeatable delivery of the AKCs. The method allowed us to focus investments toward the most important interfaces and to perform a simple variation analysis that becomes important input to the cost trade-off.

The case study demonstrated here started from an existing product and assembly decomposition. The authors feel this methodology will prove to be extremely effective in coordinating up-front concurrent design activities,

where assembly system assessments can be made early in the process once product architectures are determined and the PKC flowdown process proceeds. Specifically, assembly system planners will be able to assess different candidate assembly decompositions by identifying AKCs and utilizing the method presented here. AKCs are unique to a particular candidate assembly decomposition. Because the assembly decomposition does not always match the product decomposition, AKCs can be used to assess the effect of assembly decomposition decisions. Therefore, recognition of AKCs can allow candidate assembly systems to be evaluated based on the ability to deliver AKCs, and hence satisfy the requirements stated in the PKCs, in addition to other merits such as cost, capacity, ergonomics, etc.

The economic analysis, while not favorable on the narrowest of criteria, nevertheless points to ways that can lead to adoption of such methods in the future, especially if sufficient new business arrives.

12. Description of Demonstration Software for Assembly Modeling and Process Planning[45]

12.1. Introduction

Assembly Oriented Design (AOD) uses a number of assembly analysis tools in order to help an assembly designer plan out and analyze candidate assembly schemes prior to having detailed knowledge of the geometry of the parts involved. In this way, many assembly schemes can be inexpensively evaluated for their ability to deliver the important characteristics of the final product. This ability is important for a product design group to improve quality while shortening the product development time. The tools used in AOD are best applied to new product design, but can also be used to analyze an existing assembly and suggest areas for improvement.

12.1.1. Need

Most modern CAD systems are "part-centric" in that they are adept at helping designers create detailed geometric models of single parts on the computer screen. The datuming scheme used to create the part and features on it is normally determined by finding the scheme that allows the part to be most easily created geometrically. Often these geometric datums do not correspond to the assembly datums of the assembly into which the part fits. Careful assembly design involves coordinating assembly-level and part-level datums in a top-down way. Thus there is a need for a computer-based tool which allows designers to implement a top-down design process. Such a process would start at an assembly or final product level, define datuming schemes consistent with the important aspects of that product or assembly, and coordinate those datums down the assembly tree to the part level. In order to do this, the computer tools must support the design process with analysis that can help the designer select among the various schemes and quantitatively rank them according to defined performance criteria.

12.1.2. Desirable properties of Integrated System

In the initial stages of design, the exact design geometry is often only approximately defined. Thus an analysis system, intended to be used during this stage of design, must be able to give valid results which are independent of detailed geometry. Assembly designers are interested in evaluating how well their chosen assembly scheme will deliver important characteristics of the product such as dimensional accuracy and performance. Assemblability is also an important issue, along with the assembly time, cost of assembly, tolerances required on the parts, assembly system requirements, and others

[45] This section is adapted from [Mantripragada, Adams, Rhee, and Whitney]

specific to each assembly. An ideal system would thus support quantitative evaluation of all such criteria. Aside from the analysis capabilities, the system should be easy to use and integrate easily with other existing analysis programs such as CAD systems.

12.2. AOD Approach

In the course of this research we have defined a top-down approach to modeling and analyzing assemblies and their assembly processes. This approach is presented using a flowchart in Figure 12-1. The method presents several techniques to represent and analyze assemblies at a conceptual stage of design in an attempt to satisfy some of the needs outlined above. The process starts by carefully identifying the assembly requirements from the top level customer requirements down to the fabrication of individual parts using a method called Key Characteristics (KCs) [1]. KCs are intended to capture a few important characteristics of the product, differentiating them from the large number of un-prioritized tolerances that normally appear on engineering drawings. These KCs are expressed first as customer requirements and then translated to supporting engineering specifications for assemblies and parts. The KCs are then used to identify important datums on parts and subassemblies, and to define relationships between them. A detailed description of the different types of KCs can be found in [2].

Even though only sketches of parts might be available early in the design process, AOD can be used to define the interfaces between parts that will permit the KCs to be delivered. AOD accomplishes this by permitting the designer to define assembly features on parts. Assembly features are the local geometry regions on parts that assemble to like regions on other parts. These features are linked by a graph that defines a hierarchy among the parts, defining how the parts are positioned in space and which parts have responsibility for locating which other parts.

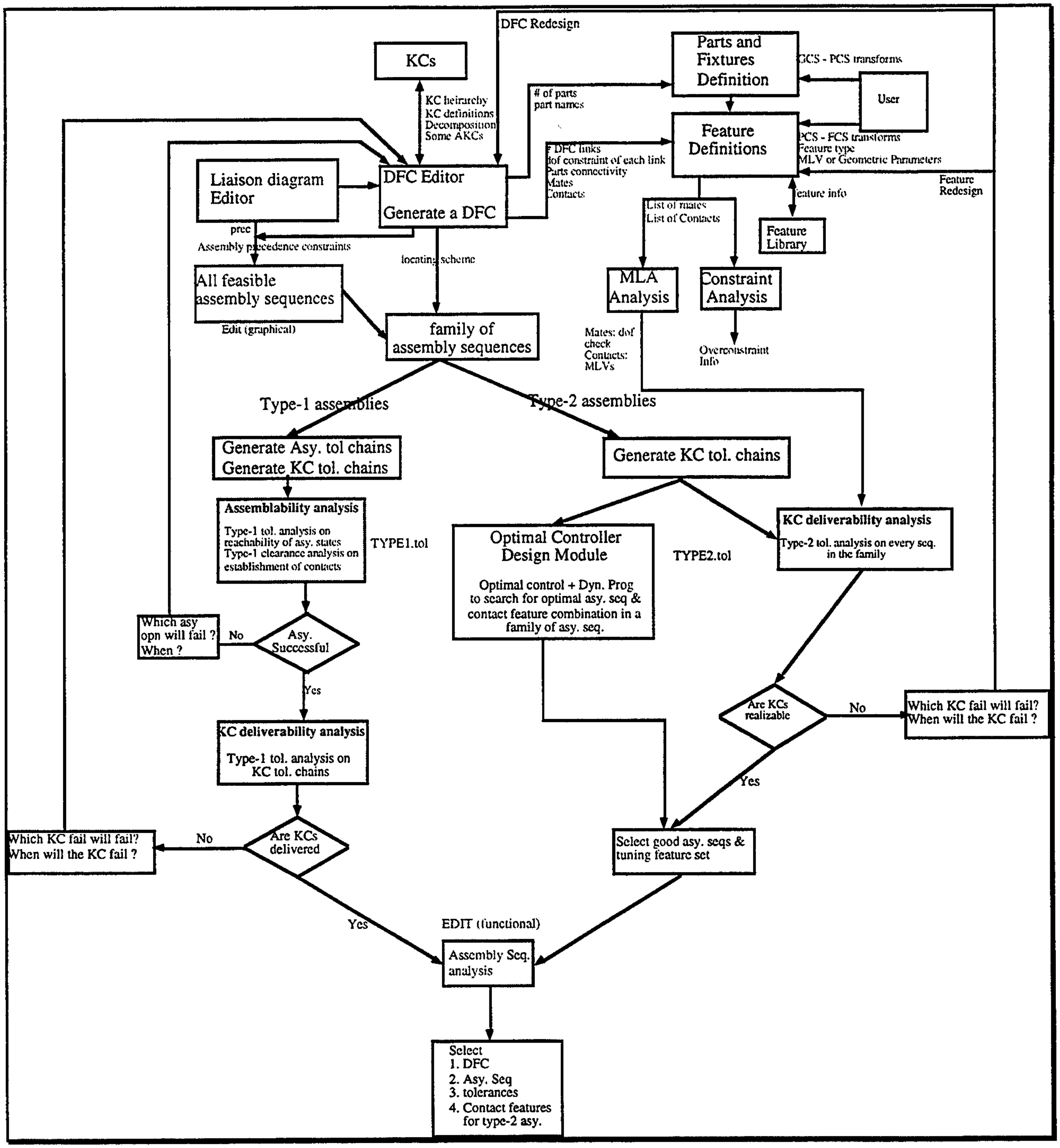


Figure 12-1: A Flowchart of the Assembly Oriented Design System

We use a technique called the Datum Flow Chain to assign this hierarchy to the datums and to define which parts locate which other parts in the assembly. A DFC is a graphical representation of the designer's strategy to locate the parts with respect to each other, which amounts to specifying the underlying structure of dimensional and datum references on parts

constituting the assembly. The theory and algorithms underlying the DFC can be found in [3, 4].

The DFC is also used to plan assembly sequences. First the complete feasible set of assembly sequences for the assembly is identified based on geometric constraints. Then the DFC is used to prune the set to a smaller set of assembly sequences based on the order of establishment of these dimensional references and the need to have only dimensionally coherent and fully constrained subassemblies. We call this smaller set a family of assembly sequences.

Candidate assembly feature sets are designed that implement the structure of dimensional and datum references imposed by a DFC. These feature sets are evaluated for complete, over-, or under-constraint.

Candidate DFCs are then evaluated and compared using criteria such as KC deliverability and tolerance analysis.

We have defined two types of assemblies, each of which require a different kind of analysis. Type 1 assemblies are typical mechanical products like engines and gearboxes. The parts for these assemblies are given their assembly features during fabrication. Type-2 assemblies are typical sheet metal items like car bodies and aircraft fuselages.

Different design and analysis procedures are employed for type-1 and type-2 assemblies. For the former, the selection of mating features is determined by considering function and is not a part of the assembly planning process. For the latter, feature type and location selection is a crucial part of the assembly process design. The design of these mating features in both types of assemblies places requirements on the assembly and fabrication processes. The DFC is then used to construct tolerance chains to perform a three dimensional tolerance analysis and choose between assembly sequences and feature sets within the most promising family identified. The end result of the exercise is a location strategy reflected in the choice of dimensional datums and their hierarchy (DFC), an assembly feature set, and an assembly procedure that satisfies the DFC hierarchy. The DFC allows the designer to explore the consequences of choosing different dimensioning, locating and fixturing schemes on the deliverability of KCs, choice of assembly sequence, assembly feature design.

In this view, design of the assembly process is driven directly by customer requirements and is implemented by selecting datum flow chains while only a skeleton of the assembly's logic and sketches of the parts exist. Detailed part geometry plays almost no role (except in the neighborhood of the assembly features), even though assembly sequence and tolerance analysis are performed. The following sections describe the different elements of the assembly oriented design approach in detail. This flowchart represents our

current best understanding of the AOD approach. It is still at an evolving stage and as new modeling techniques are developed, pieces of this flowchart too will evolve to incorporate these techniques. Section 12.3 describes the several modules in the flowchart and their characteristics. A typical design session envisioned in this AOD approach is presented in Section 12.4.

12.3. Capabilities of Current Prototype System

12.3.1. System Structure

Figure 12-2 below is analogous in layout to Figure 12-1, but shows the various software programs used to implement AOD as modules with descriptions of the information that is exchanged between each. This figure will be helpful in understanding the following discussion of the system where the program names are referred to.

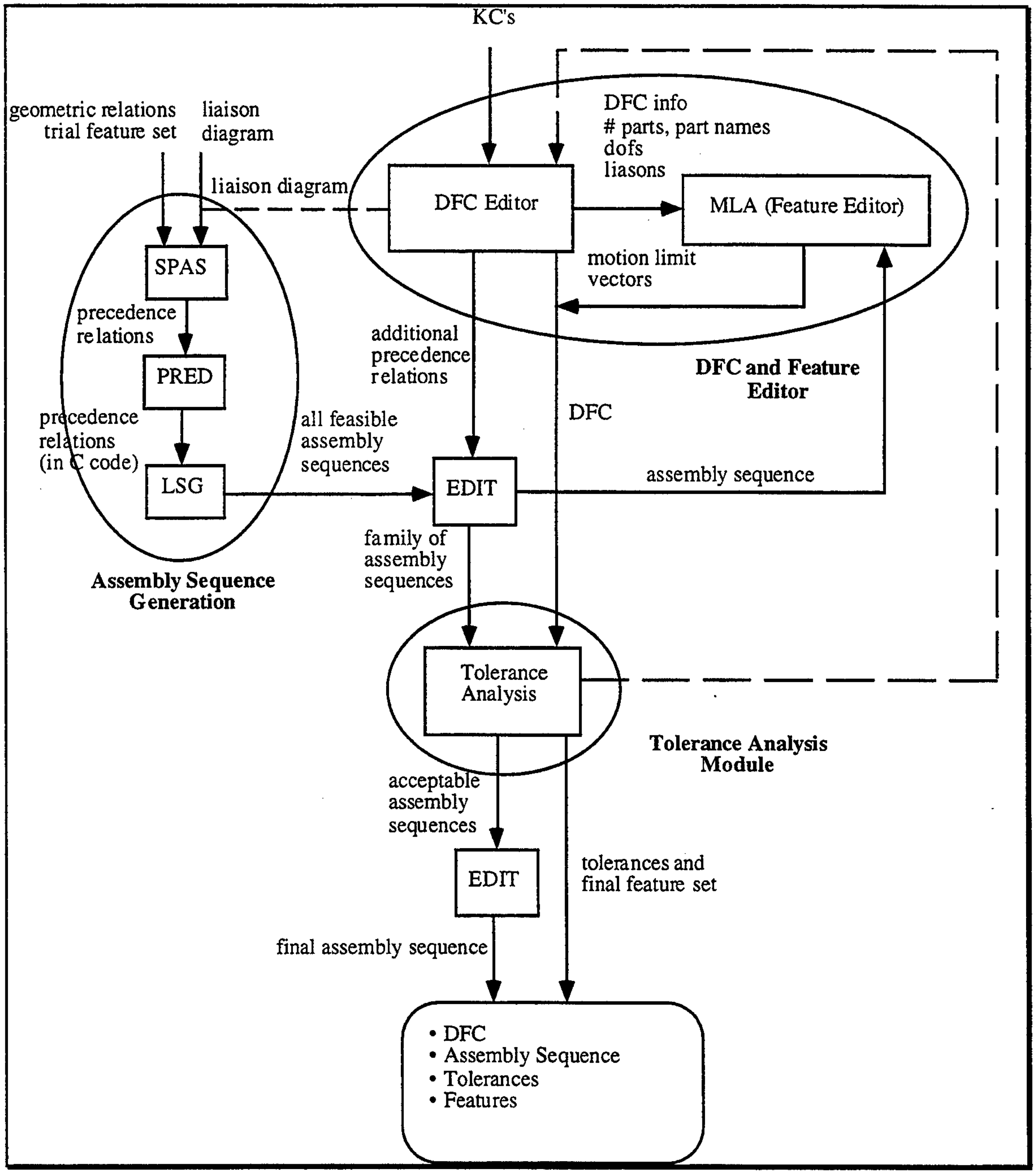


Figure 12-2: A flowchart of AOD analysis programs

12.3.2. Summary Capabilities

Using the programs shown in Figure 12-2 above, a designer is able to accomplish the following tasks:

- Design a dimensional control plan consistent with the important characteristics of the product.
- Lay out an indexing and datuming scheme that is consistent through the assembly, sub-assembly, part, and feature levels.

- Choose assembly features to realize the connections between parts and evaluate the performance of the chosen feature set.
- Generate, view, and edit all possible assembly sequences according to geometrical considerations.
- Generate, view, and edit all desirable assembly sequences that support the logic of the DFC.
- Perform variation propagation analysis on any or all assembly sequences.
- Rank the assembly sequences according to the ability of each to achieve the objectives of the KCs.

12.3.3. Synthesize an optimal set of assembly features using the DFC Editor

This is an interactive conceptual CAD tool that provides the front end of the AOD system and integrates the different modules. It has a graphical user interface that lets the designer interactively construct the DFC and liaison diagram for the assembly in the same session. Properties of the DFC and underlying theory can be found in [3]. The constructed DFC can be checked for violation of any DFC properties by performing consistency checks. These checks include detection of loops, presence of only one root node, over and under constraint, etc. The DFC editor will be linked to a program called MLA (Motion Limit Analysis) that will enable the designer to select and analyze feature sets to realize the mates and contacts. This program and its capabilities are described in the next section. MLA also allows the designer to perform constraint and motion limit analyses on these feature sets. These analyses verify if the selected mating features provide the intended constraint along the desired directions. The DFC editor also creates an assembly database where information about the DFC, liaison diagram and feature information is stored. The DFC editor is linked to the assembly sequence analysis (ASA) module. The different modules extract the necessary information directly from the assembly database. This enables generation of both the complete set and a family of assembly sequences of the assembly and DFC under design. The graphical user interface of the DFC editor is shown in Figure 12-3.

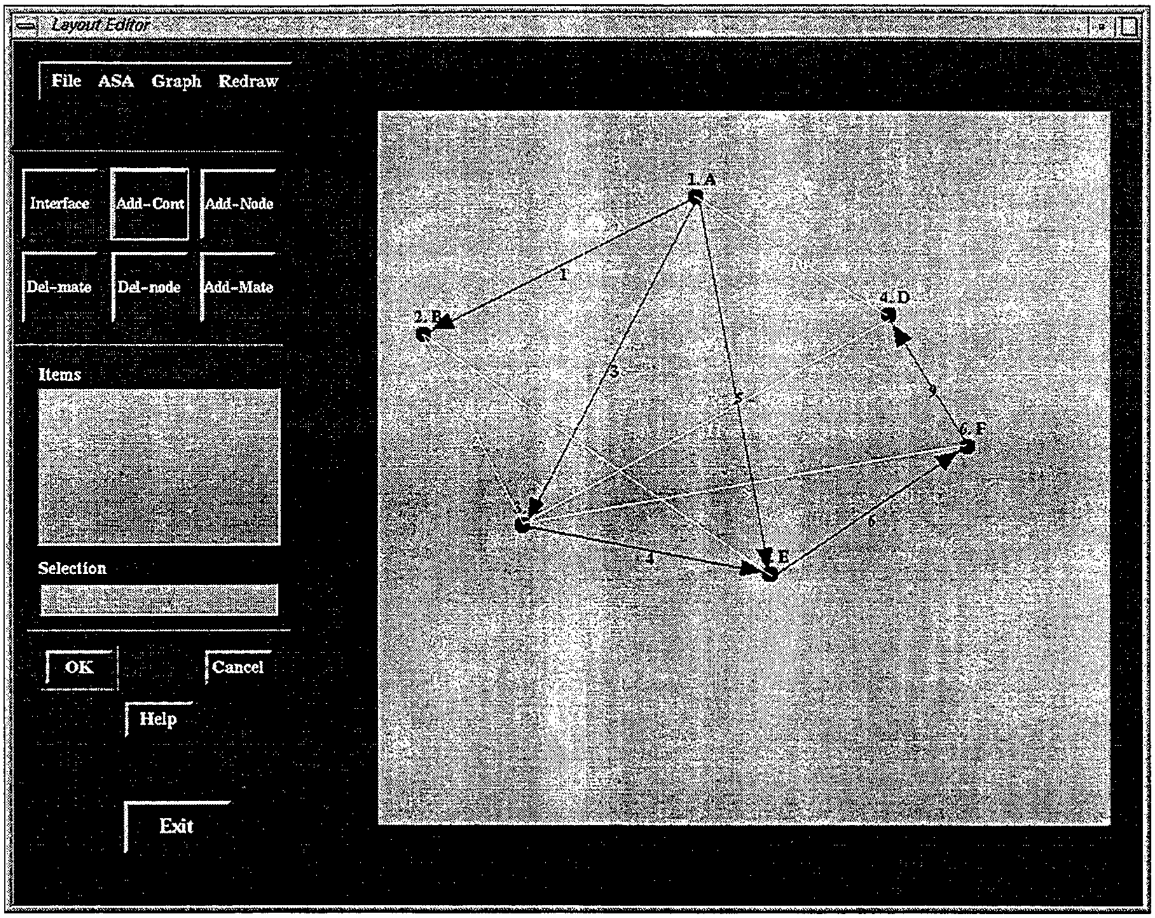


Figure 12-3: The interactive DFC editor

12.3.4. Motion limit analysis (MLA)

Motion Limit Analysis (MLA) is a tool used to support the top down design and analysis of assemblies. The purpose of MLA is to provide mathematical models of assembly features from which the ability of a feature to position one part relative to another in space can be calculated. The underlying theory behind these mathematical models can be found in [5],[12], and [13]. A user of this theory is able to obtain three major types of information about an assembly:

1. Knowledge of the directions and quantitative amounts of possible part motions of a part that is being added to an assembly at a given assembly station via connection of a defined set of assembly features.
2. Knowledge of whether or not the defined feature set over-, under-, or fully-constrains the location and orientation of the part.
3. Knowledge that the defined feature set can establish the desired location of the part within the assembly it is being added to.

The theories of MLA have been implemented in a computer software program. The MLA software receives some input from the DFC editor and some input from the user. Basically, the DFC editor provides information about the parts and interconnections between parts in an assembly. The MLA software is then used to choose features that realize these interconnections and perform calculations about the properties of the chosen set of features. Using the MLA software, a user performs four basic steps:

1. Define the location and orientation in global coordinates of all parts in the assembly under study.
2. Choose assembly features to physically realize these connections between parts that are inferred from the DFC diagram of the assembly.
3. Define the location and orientation of these assembly features on each part.
4. Specify geometric parameters defining the feature, and/or specify numerical limits on the motions that each feature will allow acting individually.

The software first analyzes all mates in the assembly. The purpose of this analysis is to check if the mates do indeed constrain all six degrees of freedom of each part as intended. The mates are also checked to see if they over-constrain the parts. Over-constraint means that a given degree of freedom of a part is being controlled by more that one assembly feature. Next the contacts are analyzed. If the assembly feature accomplishing the contact, acting independently, would allow relative motion between the two parts it connects, the limits on this rigid body motion are calculated. These limits are provided as inputs to the Type-2 tolerance analysis routine as physical limits on positional adjustments that can be made to the parts at the assembly station where the contact corresponding to each vector of limits is made. The front end interface of this program is shown in Figure 12-4.

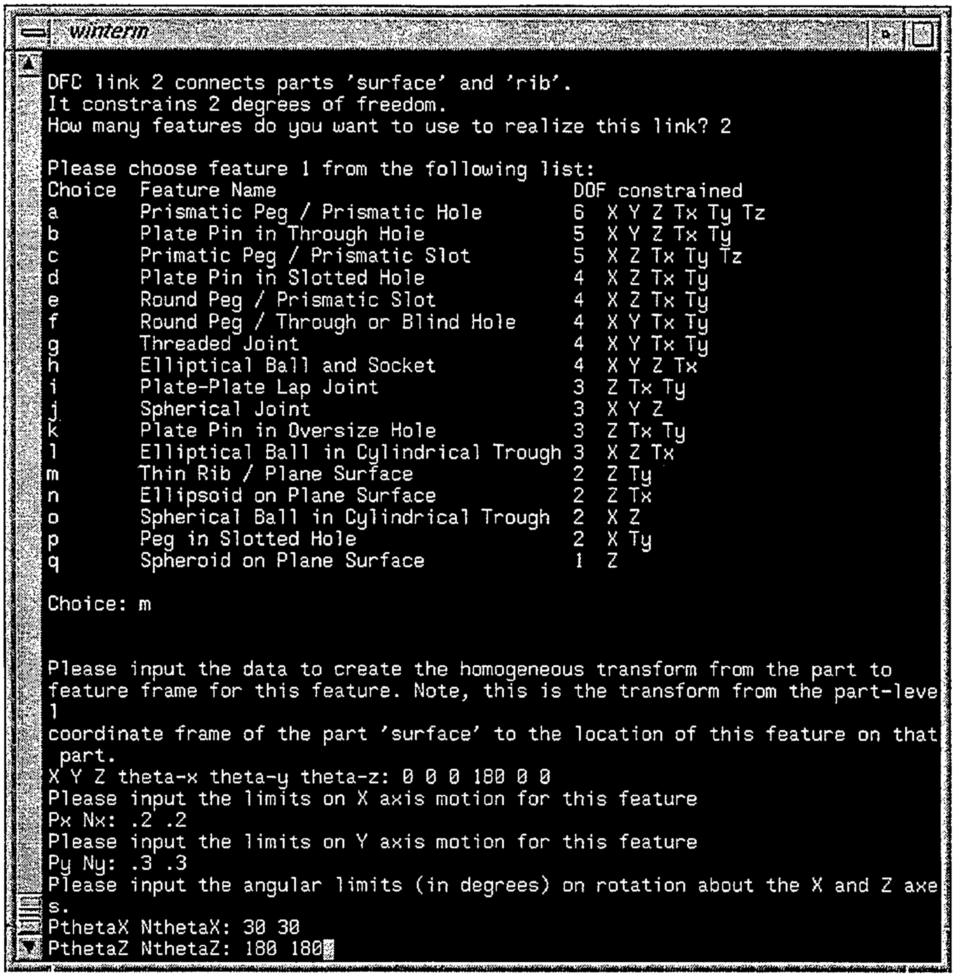


Figure 12-4: Graphical user interface of the MLA software

12.3.5. Assembly Sequence Analysis software (ASA)

This software refers to a suite of tools used to generate and evaluate assembly sequences. These tools can be used both as stand alone tools and integrated with the DFC editor. They are described as follows:

12.3.5.1. Assembly Sequence Generation

Assembly sequence generation involves first generating the assembly precedence constraints and then using the precedence constraints to generate the assembly sequences. Two types of precedence constraints are considered: geometric and DFC related.

12.3.5.1.1. Geometric Precedence Constraints (SPAS)

This software generates assembly precedence relations for the given assembly from the geometric constraints imposed by the shape and size of the

different parts in the assembly. The analysis used to generate these precedence relations is based on a graphical representation of the contacts between parts called the "liaison diagram". Each node in the liaison diagram represents a contact between parts. Three different algorithms have been implemented to generate all the possible assembly sequences. These algorithms are:

- Modified Bourjault method [6]
- Cut-Set method [7]
- Onion-Skin method

The designer is presented with a series of queries to determine the ability to assemble or disassemble a part to/from an assembly, which are answered in Yes or No. These answers are processed by the computer to generate a list of precedence relations for the assembly that are used to generate the assembly sequence diagram. The inputs to program are as follows.

- **The part drawing**

A simple sketch of the assembly showing the general shape of the parts

- **The liaison diagram**

The second input is information about the joints between parts in the assembly. As described in Section 12.2, the user constructs the liaison diagram interactively using the DFC editor. The DFC editor stores the liaison diagram in assembly database. SPAS reads this information directly from the assembly database.

- **Geometric relationship information**

The user has to specify the exact geometric relationship between parts to enable answering the queries for sequence generation.

Based on this information, assembly precedence constraints of the form

$$(i \,\&\, j) >= (k \,\&\, l)\,;$$

are generated. The operator ">=" means "must precede or concur with". The above constraint is read as: liaison i and j must be completed before or concurrently with, completion of (both) liaisons k and l (but not necessarily before or concurrently with either liaison k or l). A typical session of this program is illustrated in Figure 12-5:

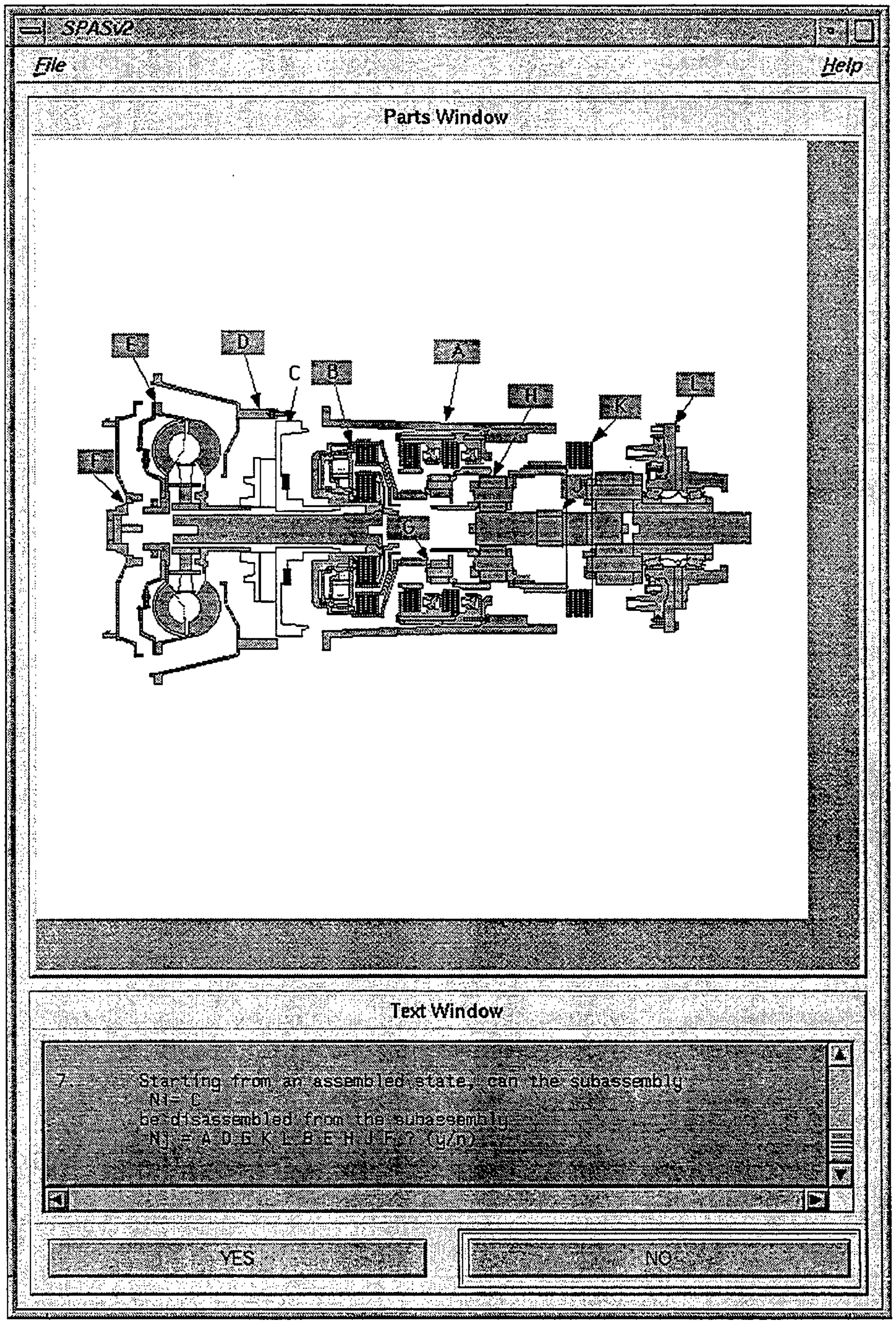


Figure 12-5: Graphical user interface of the SPAS software for generating geometric assembly precedence constraints

12.3.5.1.2.DFC Precedence Constraints (DFCPR)

A program called **DFCPR** takes the liaison diagram and the DFC under evaluation as inputs and applies the Contact and Constraint rule to generate a set of assembly precedence constraints. The liaison diagram and the DFC are

represented using incidence matrices. The precedence constraints generated by DFCPR are of the same form as the geometric constraints described above.

These assembly precedence constraints are then used by another software program to generate the set of assembly sequences that is represented using an assembly sequence graph [8]. If only the geometric precedence constraints are fed to the program, an assembly sequence graph representing the complete set of assembly sequences is created. On the other hand, if both geometric and DFC precedence constraints are fed to the program, then an assembly graph representing only a family of assembly sequences for the DFC is generated.

12.3.5.2. Assembly Sequence Evaluation (EDIT)

A software program called **EDIT** represents the generated assembly sequence graph in a graphics window where the user can interactively query, inspect, evaluate and delete assembly states and transitions based on several criteria. This software gives the designer the ability to visualize the available assembly sequences . Editing based on conditions such as: deletion of moves where a particular set of liaisons are made, specification that a particular move must immediately precede another, subassemblies hard to assemble due to accessibility problems, etc. can be applied. These editing techniques quickly reduce the number of sequences to a handful that can be subject to more detailed analysis. More details about the capabilities and functions of the EDIT program can be found in [8]. A sample session is illustrated as follows in Figure 12-6:

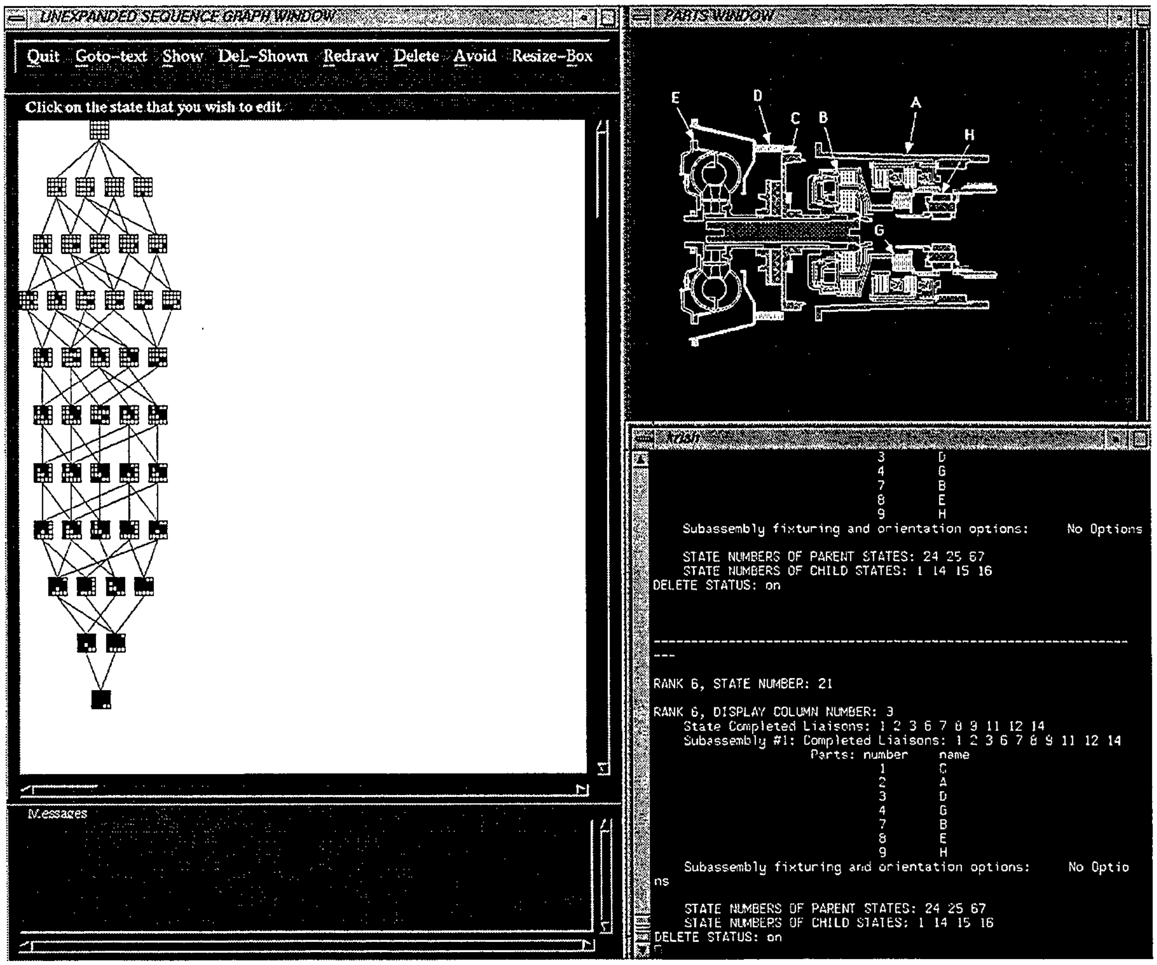


Figure 12-6: An interactive session with the EDIT software for evaluating assembly sequences

12.3.6. Control System Analyzer

The algorithms described in [9, 10] have been implemented as computer programs and can be used to evaluate assembly sequences and mating feature combinations. Two programs called TYPE1.tol and TYPE2.tol have been developed to study variation propagation in type-1 and type-2 assemblies and are described in sections 12.3.6.1 and 12.3.6.2. Interactive software implementation of the optimal controller design is described in Optimal Controller design. Currently these tools are developed as stand alone tools and require manual input to use them. In the future we foresee these tools being fully integrated within the AOD framework so that they can be used automatically by the DFC editor to analyze DFCs and assembly sequences.

12.3.6.1. Type-1 tolerance analysis module (TYPE1.tol)

TYPE1.tol is used to study variation propagation in type-1 assemblies. The input to the software is a tolerance chain for the KC that we wish to analyze. The inputs are currently provided interactively by the user and include nominal and variant transforms between coordinate frames on mating features on parts. The input and output information for this software are identical to that for TOLA which is described in [11]. We envision that the input information would eventually be extracted automatically from an assembly database for the design. The assembly database would have this information when the DFC and associated mating features describing the liaisons are designed. Currently the input window that takes this information interactively as shown in Figure 12-7.

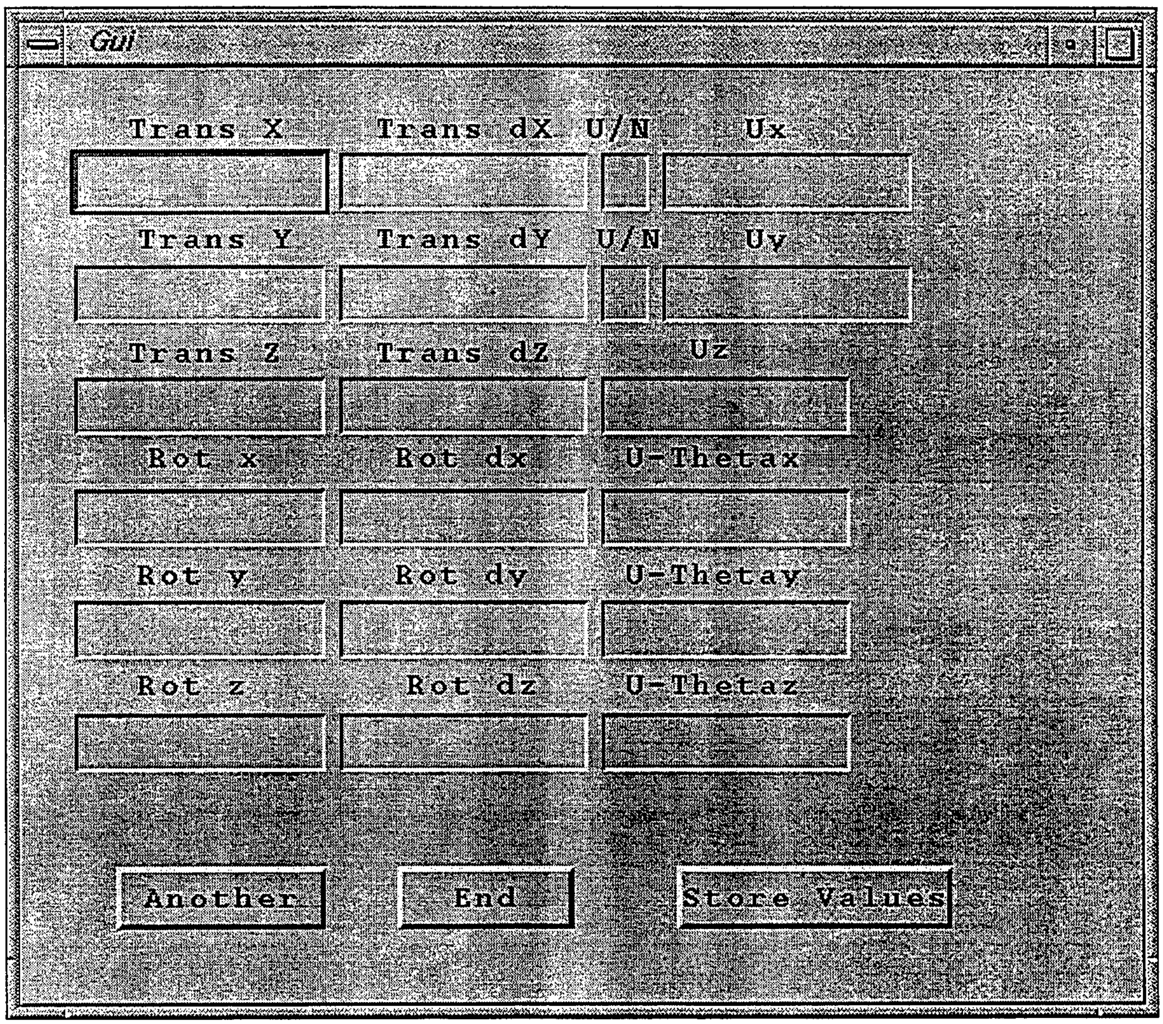


Figure 12-7: Graphical user interface of the input window that interactively takes information for every coordinate frame and provides it to TYPE1.tol

From the input information provided, the software computes the *A(k)* and *F(k)* matrices and computes the variation associated with the position and orientation of N^{th} frame with respect to the base frame. Covariance matrices for the position (V_p) and orientation vector (V_θ) are constructed and their Eigen values are computed to determine the resulting variation distribution. The Eigen values of the V_p covariance matrix are variances in the principal directions of the probability density ellipsoid. Standard deviations in each of the three principal directions are the square roots of the variances. The full lengths of these ellipsoids are equal to six times the standard deviation in the principal directions.

12.3.6.2. Type-2 tolerance analysis module (TYPE2.tol)

TYPE2.tol is a computer program that performs variation propagation analysis in the presence of a set of adjustments. It codes the algorithms described for type-2 assemblies in [10]. The inputs to this program are identical to those for TYPE1.tol except for the fact that the 6×1 adjustment vectors are also provided for each station. In places where adjustments are not possible a zero vector is input. At present, this information is provided manually by the user. In the future, we envision that the information can be accessed directly from the assembly database. The output from this program is identical to that of TYPE1.tol and is a description of the position and orientation error associated with the N^{th} frame.

12.3.6.3. Optimal Controller design module

The computer program to generate an optimal set of contact features for type-2 assemblies is developed as a part of TYPE2.tol. The inputs to this module are the same as that for TYPE2.tol except for the fact that no adjustment vectors $\tilde{U}$ are provided as inputs In addition the user interactively provides the **Q(k), R(k),** and **S(N)** weighting matrices to define the optimization function. The significance of these matrices is described in [10]. Based on the inputs and weighting matrices, the program computes an optimal set of $\tilde{U}$ vectors which are to be interpreted by the user to design contact features. The program also determines the resulting variation distribution associated with the N^{th} frame given this set of optimal adjustments. An interactive session for the program shown in Figure 12-8.

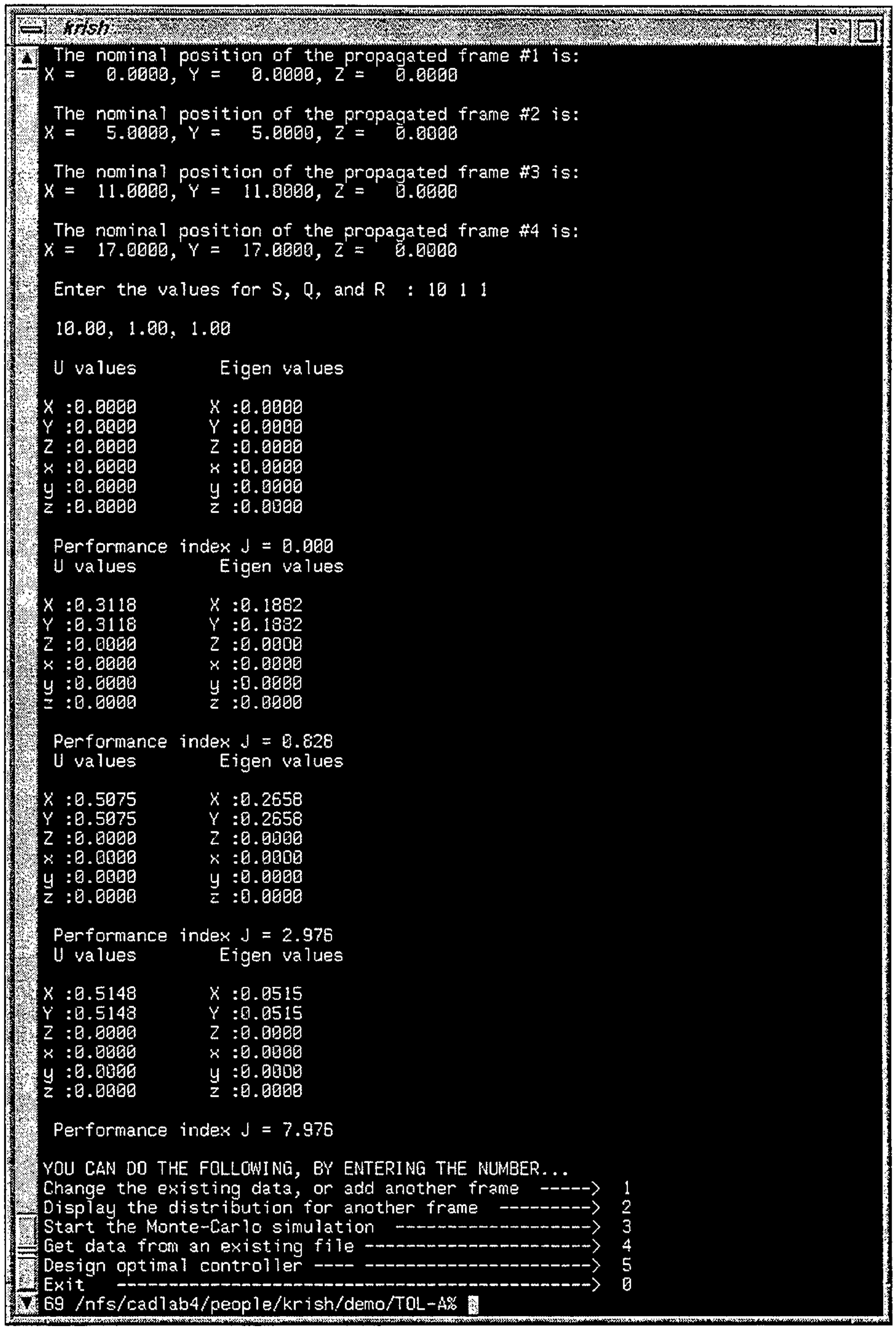


Figure 12-8: Example interactive session with the control theory analyzer

12.4. Design Session

In this section we present a description of how we envision a designer would use AOD system. A step through the flow chart presented in Figure 12-1 is presented below:

1. The first step in the design process is the construction of the assembly's liaison diagram and DFC. A detailed flowdown of the key characteristics for the assembly is a pre-requisite for this operation. We assume that identification and classification of KCs is provided to us as input. Based on the KCs for the assembly, the designer interactively constructs a DFC and liaison diagram for the assembly using the DFC editor. The DFC editor creates an assembly database and stores information about the DFC and the liaison diagram for the assembly. Several types of consistency checks can be preformed on the DFC created to verify if it satisfies all the properties of a DFC as described in [3].

2. At present, we assume that the designer has rough sketches of the assembly to work with. In the future, we envision the DFC editor to be linked with a sketching CAD tool that will permit the designer to construct preliminary geometry of the parts in the assembly at an abstract level. This CAD tool will also be linked to MLA software described in 12.3.4. The next step is to design the mating features for the mates and contacts in the assembly. This is done using the MLA software. MLA reads information about the parts and fixtures, connectivity between parts, and DOFs constrained by mates directly from the assembly database. Using MLA the designer defines the features that constitute the mates and contacts for the assembly. Different kinds of analyses such as determination of over and under constraint conditions and motion limit analysis for contact features are performed using the MLA program. Motion limit analysis determines the absorption zone for every contact feature set in the assembly and stores them in the assembly database. For type-2 assemblies, these are the $\tilde{U}$ vectors used by the TYPE2.tol to perform variation propagation analysis in the presence of adjustments.

3. The next step involves planning assembly sequences for the assembly. The DFC editor is used to spawn the ASA module to generate a complete set of assembly sequences for the assembly. This is done by first executing SPAS to generate geometric precedence constraints and then using these constraints to generate the assembly sequence graph. The assembly sequences are visualized using EDIT. Next a family of assembly sequences is generated by first executing DFCPR and appending the DFC constraints generated by DFCPR to those generated by SPAS. This new set of constraints is used to generate a family of assembly sequences which is also visualized by EDIT. All these operations are fully integrated within the DFC editor framework.

4. The next step is to evaluate the family of assembly sequences. As described in [3], the family can be evaluated using several criteria. The one of prime importance is variation propagation. For type-1 assemblies, TYPE1.tol is used to study variation propagation to address assemblability type problems. In type-1 assemblies all assembly sequences in a family of assembly sequences yield identical results in variation propagation analysis. Hence only one assembly sequence from the family need be analyzed to evaluate a complete family of sequences. As described in 12.3.6.1, the inputs required for TYPE1.tol are the assembly tolerance chain and transform information. At present, TYPE1.tol runs as a stand alone piece of software and the user provides the input information interactively to perform the analysis. In the future, this program will be integrated to the DFC editor as most of the needed inputs already exist in the assembly database in one form or another.

5. For type-2 assemblies, TYPE2.tol is used to perform variation propagation in the presence of adjustments. Again, at present this program runs as stand-alone software. The inputs to this program are the same as those for TYPE1.tol except that the absorption zones of the various contact features also need to be provided. As described

in section 12.3.4, this information is generated by the MLA software that determines the numerical limits on the motions that each contact feature will allow. Here different sequences within a family need to be evaluated with respect to each other for any given set of contact features.

6. For type-1 assemblies, based on the results obtained from TYPE1.tol, the designer may choose to redesign the elements of the DFC or tolerances on mating features. In the case of type-2 assemblies, the designer can choose to redesign the DFC, redistribute tolerances on mating features or select an alternate set of contact features. The designer may also choose to run the optimal controller design module to design an optimal set of contact features that will repeatedly deliver the KCs.

7. The resulting family of assembly sequences and feature sets can then be evaluated for other assembly planning criteria such as desirable subassembly states, desirable assembly transitions, existence of multiple subassemblies, sequence of establishment of liaisons, etc using the EDIT software.

8. The above process can be iterative and is performed until the designer is satisfied with the assembly design. At the end of the whole process, the designer will be left with a DFC for the assembly, a set of assembly features, a desirable assembly sequence and a measure of the probability of the design and assembly process delivering the KCs repeatedly.

9. For assemblies involving multiple assembly stations, a DFC is constructed for each assembly station. In such cases, the above seven steps are performed for each assembly station. The entire assembly process is thus modeled using a series of clusters of assembly operations.

12.5. Conclusion and Future Work

12.5.1. Distributed design environment

With product development activity becoming increasingly global these days, there is a general shift towards network based design tools to permit dispersed teams to work together. We foresee that CAD tools in the future will be a lot more web based and network centric. Some of the applications described above have been developed to run under a distributed type of environment. The ASA software has been developed to use a WWW browser such as Netscape or Internet Explorer as a front end and can be used by remote users to analyze assemblies. This work was done as a part of the ACORN (Advanced Collaborative Open Resource Network) project. Server scripts were developed that fork these applications and present the user a form based environment to interactively generate, inspect, edit, and evaluate assembly sequences. The front-end interface developed to run EDIT on the World Wide Web is shown below in Figure 12-9.

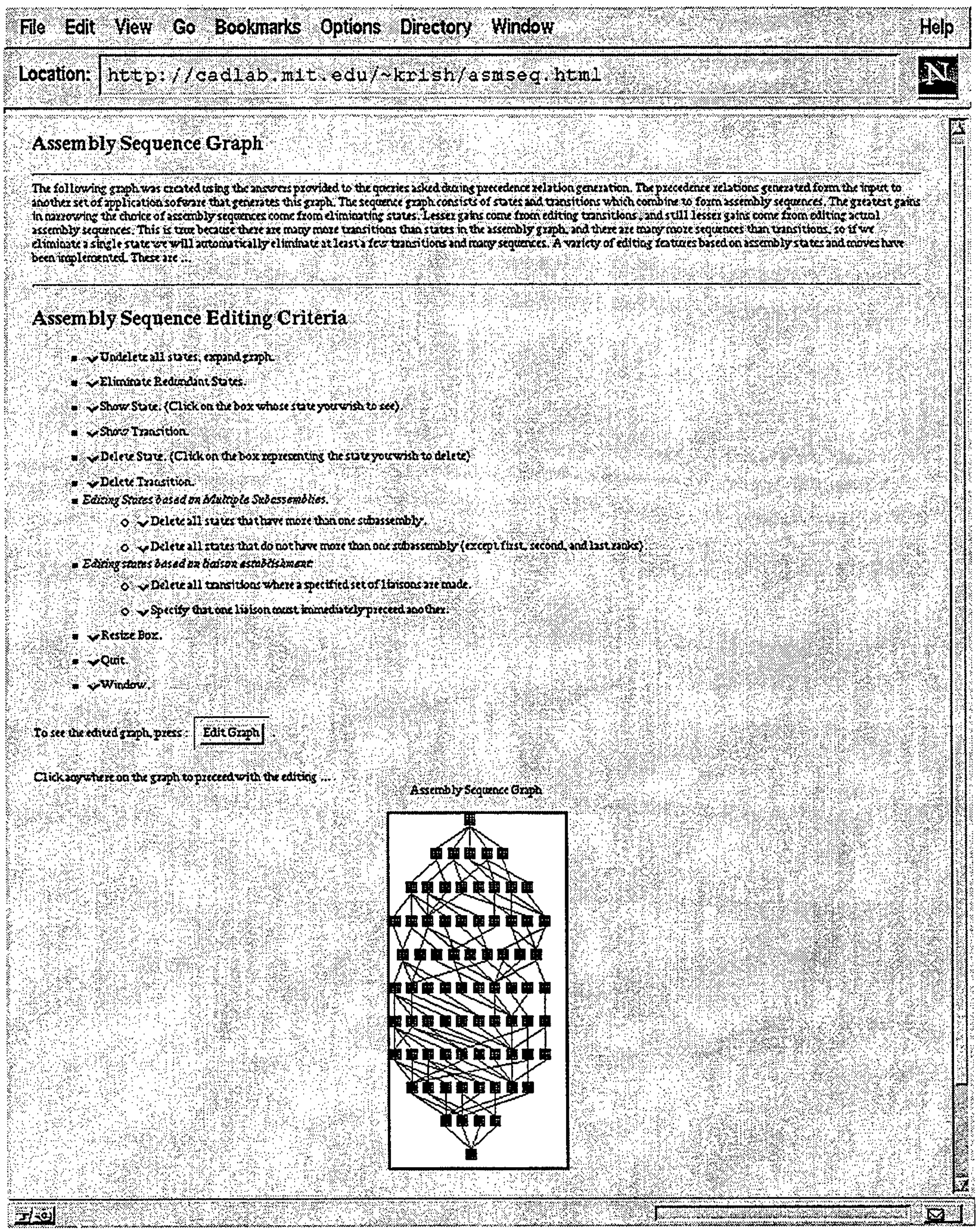


Figure 12-9: Assembly modeling services in a distributed web based environment

In future, we shall see the applications having a lot more web based content to make the Assembly Oriented Design environment a true distributed design environment so that dispersed teams can be involved in different aspects of the assembly design.

12.6. References

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[9] R. Mantripragada and D. E. Whitney, "State Transition Models of Mechanical Assembly Processes," *Submitted to IEEE Trans. on Robotics and Automation*, 1997.

[10] R. Mantripragada and D. E. Whitney, "Modeling and Controlling Variation Propagation in Mechanical Assemblies using State Transition Models," *Submitted to IEEE Trans. on Robotics and Automation*, 1997.

[11] O. L. Gilbert, "Representation of Geometric Variations using Matrix Transforms for Statistical Tolerance Analysis in Assemblies," in *S. M. Thesis, Mechanical Engineering*. Cambridge, MA: MIT, 1992.

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[13] R. Konkar and M. Cutkosky, "Incremental Kinematic Analysis of Mechanisms," *Journal of Mechanical Design*, Vol. 117, December 1995, pp. 589-596.

13. Concluding Remarks

13.1. New design methods and tools

This project developed a series of new product development tools aimed at increasing the agility of manufacturing and assembly operations by preparing high leverage information during design. This information emphasizes integration, information flow mapping, and capture of integration-oriented design intent. The tools include

• A method for exposing the integral character of concept designs and comparing such designs for relative amounts of integration risk

• A method for modeling assemblies and designing their dimensional control so that Key Characteristics delivery can be planned systematically

• A method for evaluating Key Characteristics programs at companies and comparing their relative maturity

• A variety of mapping methods including contact chains and Design Structure Matrices that aim at making interconnections between mechanical parts, people, and information obvious to people who work with them

13.2. Implementation issues

It has become clear during this research that integration issues are difficult for companies to make progress against. Many technological, managerial, and cultural barriers prevent integration from occurring, and the same barriers encourage local behavior and knowledge. The research shows clearly that companies must be very pro-active if integration of product design and manufacturing in general and specific domain knowledge is going to occur. Very high level management support is necessary for extended periods of time. Any number of technological solutions can be proposed and tried, but they will not get far if the reward systems of the company encourage local behavior. In addition, there is undoubtedly increased cost and effort required during design to support integrative activities. The rewards for these activities are received by others at later times, even during subsequent programs. Special efforts are needed to sustain integrative activities in the face of such barriers.

13.3. A strawman maturity model for assembly management

Design for assembly has been around for 20 years and yet many companies have not made much progress in reaping its benefits or moving beyond it with methods of their own. We have found companies at the following levels of "maturity:"

1. Parts are designed using any number of different kinds of CAD methods but there is no attempt to coordinate their design from an assembly point of view.

2. An informal KC methodology exists, attempting to determine customer requirements and "flow them down" to individual assemblies and parts, but the method of identifying KCs and decomposing them depends on past experience and resembles fighting the last war.

3. A more systematic approach to KCs and assembly coordination exists, which includes involving tooling designers relatively early in the design process. Parts, assemblies, and tooling are designed more or less together so that fixturing points and datums agree from part to part.

4. Under one management organization, assembly design, tooling design, toolign procurement, and outsourcing of parts are all managed together, creating a shared database of designs, datums, intent, measurement plans, and mutual committments.

In our experience, the majority of companies are at level 2, with a few at level 3. It is surprising how many are at level 1 and how few are at level 4.

It is our hope that this research will be helpful to companies in improving their agility in this area.

14. Appendix 1. Outline of Course in Mechanical Assembly and its Role in Product Development

This appendix contains informatin about a course in assembly that was developed during the research. It contains most of the new material developed over the course of the project. The first element is the syllabus consisting of the class schedule, lecture topics, and reading assignments. The second element is the set of project assignments carried out by the students during the semester. The third element is a summary of the step by step process taught during the course covering design for assembly.

2.875 Mechanical Assembly and Its Role in Product Development
Fall 97
Dr Daniel Whitney

Week #1	1	Introduction
Th	4-Sep	No reading
		Videos: Computer controlled assembly of alternators, Sony SMART System
		Lecture: Overview, context history, logistics
		Relation between assembly and system engineering
		Role of assembly in product development
		Manual and machine assembly issues and contrasts
		Summary of step by step assembly analysis process
Week #2	2	Assembly in the small: basics of rigid part mating theory; insertion force models, wedging, jamming
Tue	9-Sep	Readings:
		1. Computer-Controlled Assembly, <u>Scientific American</u>, Feb 78
		2. Force Feedback Control of Manipulator Fine Motions
		Video: Touching experiences
		Lecture: basic strategy of active compliance & basic matrix representations of assembly
		Statement of step-by-step process for "assembly in the small"
Th	11-Sep	Assembly in the small: rigid part mating theory
	3	Readings
		1. Quasi-static Assembly of Compliantly Supported Rigid Parts
		2. Hi-T Hand paper: Takeyasu, Goto, Inoyama
		Lecture: basic statics analyses, demos of insertion force software, notion of passive compliance
		Computer program for rigid part mating insertion force
		Hand in project description
Week #3		Basics of compliant part mating theory; insertion force models of single and multiple parts; wedging; "optimum chamfers", experimental methods and instruments
Tue	16-Sep	Compliant part mating theory
	4	Readings
		1. Designing Chamfers
		2. Intro & Part Mating portion of Ford Rear Axle report, Draper C-5292, pp i - 16.
		Lecture: basic statics models, discussion of electrical connectors, multiple mates, tolerances
		Class demo with assy descr worksheet
Th	18-Sep	Force sensors and experimental methods
	4	Readings
		1. DL P-176 (Force sensors)
		2. Gerard Piller's Force Sensor Paper in "Robot Sensors" by Alan Pugh, pp 67-74
		Lecture: Instrumentation, experimental methods, illustrations from AMP and part mating data
		Computer program for compliant part insertion force
		RE-iterate matrix approach
		Project report #1: completely describe the product
Week #4		
Tue	23-Sep	The Remote Center Compliance - history, theory, and practical realizations
	6	Readings
		1. Draper P-364
		2. Concurrent Design of Products and Processes Ch 7: RCC & compliant assembly strategy
		3. "The IRCC Instrumented Remote Centre Compliance," pp 33-44 in Robot Sensors by Alan Pugh
		Lecture: derivation of RCC properties in part mating, review of basic conditions for passive assy use of RCC in engines, force fits, precision assembly
		Decoupling task accuracy needs from machine/robot accuracy capability
		Part mating paper JDSMC portion on RCCs
		Example uses of RCCs in practice. Various stories. Description and use of Instrumented RCC
		Gillette Sensor Razor as an RCC
		RCC patent slides

Th	25-Sep 7	DFA Theory Readings: 1. Redford & Chal: Design for Assembly, pp 96-134 Lecture: conventional DFA pro and con Time for discussion of student projects 1000:1 feature ratio betw process and product Redford pump redesign slide
Week #5		
Tue	30-Sep 8	DFA Practice Readings: 1. Ulrich et al "A Framework for Including the Value of Time in DFM Decision-making" 2. Concurrent Design pp 433-35 (ASDP Chart) and 471-93 (a/c case study) Axle redesigns, modularity study Greg Blonder video on product analysis
Th	2-Oct 9	Assembly in the large: basic issues of physics and economics; product architecture; DFA in the large; commonality, carryover, and reuse Readings: 1. Whitney Harvard Business Review article "Real Robots Do Need Jigs" 2. Whitney Harvard Business Review article: "Manufacturing by Design" Description of the step-by step process for "assembly in the large." Class exercise with a real product: product character, types of assembly environments Sewing, "environment" issues **Project report #2: choreograph each assembly step and perform a DFA analysis**
Week #6		
Tue	7-Oct 10	Product Architecture, flexibility Readings: 1. Whitney paper "Nippondenso: A Case Study of Strategic Product Design" 2. Ulrich & Eppinger Product Design and Development Chapter 7: Product Architecture. Lecture: product architecture and its relation to assembly Discussion of Gerwin's 7 kinds of flexibility Power line splice example Redford product structure examples and their relation to architecture and flexibility Airbus architecture dilemma
Th	9-Oct 11	Assembly in the large: Workstation design issues Readings: 1. CD book Chapter 11 2. System portion of Ford Rear Axle Report, Draper C-5292, pp 17-31 Workstation layout, timing, feeding methods, tools Class example Possibilities: power line splice ignitor alternatives; clutch plate station alternatives
Week #7		
Tue	14-Oct 12	Math models of assemblies: 4x4 matrix representations; assembly features and data models; examples of how current CAD systems represent assemblies Readings: 1. Introductory 4x4 math from Paul's book 2. Whitney The Potential for Assembly Modeling in PD (On Whitney's home page: http://web.mit.edu/ctpid/www/Whitney/papers.html Lecture: Feature-based modeling of assemblies using 4x4 matrices; assy modeling in PD Discussion of top-down and bottom-up assembly modeling Video: Feature-based Design for Assembly
Th	16-Oct 13	AITL System Design Issues Readings: 1. Concurrent Design Ch 10 2. Handbook of Industrial Robotics: chapters 65 and 66 (assy line and station examples) What assembly lines, robots, and assembly automation equipment look like, how they work, and what some of their design problems are Descriptions of lines, basic elements, kinds of layouts, rules, constraints Sony FX-1, ND alternator line, Boeing 777 floor layout

Week #8
Tue 21-Oct Field trip to see assembly equipment in use or being made
14 Gillette Sensor Razor manufacturing plant
Th 23-Oct Midterm presentation of student projects covering first three reports
15 **Project report #3: Design a workstation**

Week #9
Tue 28-Oct Assembly system design techniques
16 Readings:
1. Handbook of Industrial Robotics chapter 63, pp 1060-1070 (system flow, timing)
2. Concurrent Design pp 426-449 (system synthesis)
Lecture: layouts, procedure, ASDP Exercise

Th 30-Oct Assembly sequence analysis and examples
17 Readings:
1. Memo MAT 1314 "Bourjault's Assembly Sequence Method"
2. Memo MAT 1326 "Bourjault's Method for Assembly Sequence Analyis" (read through p8)
3. Baldwin-Abell paper on assembly sequence generation system (skim)
Lecture: basic notion of assy seq design; derivation of Bourjault algorithm, examples, stories
Examples, illustration of assembly feature info, some of Jeff's stuff on mate constraints
Video of Assy Seq Analysis
Demo of SPAS software in CADLAB

Week #10
Tue 4-Nov Discrete Event Simulation
19-Jan Guest lecturer
Reading:
1. Concurrent Design Ch 15 (simulation)
Th 6-Nov Tolerance buildup in assemblies
19 Readings: (You can skim the first two as long as you get the idea)
1. Wang and Ozsoy, Representation of Assemblies...
2. Whitney, Gilbert, Jastrzebski, Representation of Geometric Variations Using Matrix Transforms
3. Muske, Application of Dimensional Management on 747 Fuselage
4. Sweder & Pollack, Full Vehicle Variability Modeling
Lecture: basic relationships between part and assembly tolerances, assembleability analysis
Project report #4: create a floor layout

Week #11
Tue 11-Nov Holiday: no class

Th 13-Nov Economic analysis of assembly systems
20 ROI, DCF, basic unit cost models
Reading:
1. Concurrent Design Ch 12, pp 345-357, pp 335-343
2. Boothroyd "Assembly Automation and Product Design" pp 197-228
3. Economic Analysis portion of Ford Rear Axle report, Draper C-5292, pp 32-42
Lecture: basics of economic analysis, investment, savings, return
Reuse of existing lines and parts, flexibility

Week #12
Tue 18-Nov Key Characteristics, outsourcing, supply chain management
21 Readings:
1. Fine & Whitney: "Is the Make-buy Decision a Core Competence?" (On Whitney's home page)
Lecture: relation between architecture, assembly, outsourcing, KCs
Th 20-Nov The datum flow chain
22 Readings:
1. Cunningham et al: "Definition, Analysis, and Planning of a Flexible Assembly Process"
Definition and properties of DFCs
Discussion of 767 study
Comparison of wing assembly at Boeing and Airbus
Reprise of Airbus architecture dilemma
Project report #5: Do economic analysis of this floor layout

Week #13			
Tue	25-Nov	23	Type 1 and type 2 assemblies (car engines and transmissions, car bodies, airplane fuselages, selective assembly) Readings: paper by Krish on Datum Flow Chain, including definition of Type 1 and Type 2 assemblies to be handed out the class before. Lecture: type 1 and type 2 assemblies, examples More discussion of 767 study
Th	27-Nov		No class
Week #14			
Tue	2-Dec	24	Role of architecture choice in concept design Readings: Paper by Tim to be handed out the class before
Th	4-Dec		Project presentations **Project report #6: discrete event simulation of this layout**
Week #15			
Tue	9-Dec		Project presentations

PROJECT ASSIGNMENTS

1. Completely describe the product
   - draw all the parts freehand or 2D computer
   - number all the parts for easy reference and make a parts list
   - make an assembly drawing showing the parts either in an exploded view or assembled
   - determine what materials they are made of
   - list and discuss all the mates
   - measure clearances
   - estimate difficulty of assembly using clearance ratios
   - if possible, determine differences between different models of the product

2. Completely choreograph each assembly step in any convenient assembly sequence and identify:
   - required gross motions including reorientations
   - required fine motions
   - features on parts where they can be gripped
   - features on parts where they can be mated to a fixture
   - all chamfers and lead-ins or indicate where there are none
   - classification of all fasteners
   - auxiliary operations such as lubrication, test, and inspection
   - possible problems and risk areas
     - feeding, fixturing, presenting, orienting
     - gripping
     - inserting
   - sketch the fixtures and grippers that are needed for assembling this product
   - perform a DFA analysis using any of the methods from the readings
   - suggest design improvements
   - if feasible, implement some of these changes on an example part or parts

3. Design one or more workstations
   - determine required cycle time to complete the operation or operations planned
   - lay out the station, including in- and out-flows of assemblies and parts
   - plan required motions of equipment or people
   - show how necessary inspections or tests will be carried out
   - allocate required time of each activity and draw on a Gantt chart for a complete cycle
   - estimate the purchase and installation cost of this station
   - estimate the cost of performing one assembly cycle

4. Create a floor layout for this product's assembly
   - generate some feasible assembly sequences, choose one, say why
   - draw assembly trees for some assembly sequences, identifying subassemblies
   - assume a production rate, annual volume, or cycle time
   - assume workstations or people with given realistic assembly speeds
   - draw or sketch the floor layout, showing where each workstation is and what steps it does
   - show how parts will flow across the floor to feeding stations along the line
   - provide space for any people who work on the line, keeping them clear of machinery
   - if software is available, use it to design the concept line

5. Perform an economic analysis of this assembly layout
   - estimate or obtain approximate costs of equipment and labor rates with OH and benefits
   - estimate engineering and installation costs
   - establish a payback period or required rate of return
   - determine unit assembly cost
   - determine ROI

6. Perform a discrete event simulation of this line
   - diagram the line with activities and queues
   - write program and make several runs
   - identify any operating problems and improve the design

Systematic Assembly Analysis and Planning Process

Understand context (addressed in more detail later)
- management's objectives for the product or product line
    - production volume
    - cost
    - quality
    - model mix or evolution
    - schedule for going into production
    - status of the design: new, reused
- character of the product, nature of the market and customers
    - customer expectations
    - nature of customer interaction with the product
    - reuse, upgrade

Assembly in the Small

- Understand each assembly step in detail
    - the basic requirements
        - size, shape, weight, dimensions of each part
        - characterization of each mate between parts
        - special character of particular parts
    - assembly difficulty
    - handling constraints
        - gripping
        - feeding
- Conventional Design for Assembly
    - part consolidation opportunities
    - part feeding difficulty
    - part handling difficulty
- Identify high risk areas
    - part damage
    - wrong part
    - misassembly
    - safety or regulatory issues
    - tasks so hard only one person can do them
- Identify necessary experiments
- Recommend local design improvements

Assembly in the Large (aka Design of Assembly)

- Understand the business context
  - product character and type of market
  - sales volume anticipated
  - model variety anticipated
  - plans for new versions
  - delayed committment
  - supplier logistics and make vs buy
  - cost limits
  - labor costs and any regulations
  - cost calculation and ROI methods
  - ROI targets
- Understand the factory context
  - labor conditions, training, shift policies
  - space and facility constraints
- Identify system requirements
  - tentative cycle time
  - production flow and floor layout
  - feasible methods and equipment
  - required sensing and communication
  - required displays and controls
  - parts presentation
  - alternate assembly sequences
  - fixtures and parts carriers
- Design a concept assembly system
  - system architecture
  - equipment selection and task assignment
  - cost and economic performance
  - simulation
    - average flow and production rate
    - uptime
    - queues, blockage, starvation
    - model changeovers
- Make final recomendations
  - additional design improvements
  - line design or sequence options
  - remaining risk areas